CLIMATIC ASPECTS OF HIGH DENSITY URBAN HOUSING IN THE WARM-HUMID TROPICS:

With Particular Reference to Dacca.

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ABSTRACT.

This thesis attempts to investigate systematically the climate-built form relationships relevant to the criterion of human physical comfort in an indoor space and express those in convenient forms to be useful in design. The architectural problem under consideration is high density urban housing in a warm-humid climate with particular reference to Dacca.

The research involved inquiries into a number of different areas. Firstly, the problem of urban housing in the tropics was examined with particular reference to the conditions in Dacca. It was found that high density developments, especially in the urban housing sector, was highly imperative from the view points of the rapid urbanization and the scarcity of land available for urban use. Also from an appreciation of the given constraints it was found that a flat-type development with rectilinear geometry was appropriate under the given conditions.

Secondly, the requirements for human physical comfort in an indoor space and the methods of defining a comfort zone were investigated. It was found that the bio-climatic chart was a useful and convenient way of defining a comfort zone. Accordingly, the bio-climatic chart for the tropics reconstructed by Koenigsberger _et al._ (1974) with revised values according to the Australian CEBS findings was used for defining the comfort zone for Dacca.

Thirdly, the interactions between climatic forces (the sun and the wind) and the built form were analyzed in relation to human physical comfort in an indoor space. Through these analyses a set of relevant performances of the form and their measures as well as a set of appropriate descriptors of the form and their measures were formulated.

Fourthly, the form-performance relationships, i.e. variations in the values of the measures of the performances of the form corresponding to variations in the values of the measures of the descriptors of the form were investigated. As far as the solar radiation was concerned, the investigations were carried out on a theoretical basis. For the wind, however, experimental investigations in a wind tunnel were carried out in addition to the theoretical treatment of the form-flow relationships. The results of the experiments, presented in a simple graphic form, not only conveyed useful information for the design problem we are concerned with but also indicated that the experimental approach was worthwhile for further investigations involving more variations in the parameters of the form and the flow characteristics.

Finally, the design applications of the form-performance relationships (i.e. the design aids) were discussed and illustrated in relation to the given problem demonstrating the usefulness and convenience of the aids in practice. The point, however, was made that architecture today is expected to respond not only to climate but also to a series of other complex requirements which often dominate design decisions. The ultimate responsibility for the form rests with the designer because he is the one who conceives a possible solution in the first place, verifies and modifies it in stages, making compromise decisions whenever necessary and reaching ultimately to the proposed solution.

CONTENTS:

PART 1

INTRODUCTION,

DESCRIPTION OF THE PROBLEM AND

THE APPROACH

1.1 A GENERAL INTRODUCTION

Tropical housing, particularly housing in the urban areas of the tropics, is a major problem concerning millions of people in many developing countries. Socio-economic and demographic factors are primarily responsible for the deplorable state of urban housing in the tropics. Along with quantitative and qualitative inadequacies of various kinds, housing for the rapidly growing urban population of the tropics often exhibits utter disregard for the regional and climatic considerations necessary for ensuring fulfilment of the basic needs of human physical comfort and sanitation in the built environment.

Historically, the building of shelter originated from the two basic human needs - protection from the 'more inimical natural elements, predators and the like' and provision of an atmosphere favourable to social and spiritual endeavour. Even though it has been argued (Rapoport, 1969) that socio-cultural forces are the primary generators of dwelling forms and that 'buildings and settlements are the visible expression of the relative importance attached to different aspects of life and varying ways of perceiving reality', one cannot fail to see and appreciate how climate has been reflected in the structures man has been building for himself through history. The ancients recognized that regional adaptation was an essential principle of architecture. Vitruvius wrote in De Architectura (Granger, 1934): "For the style of buildings ought manifestly to be different in Egypt and Spain, in Pontus and Rome and in countries and regions of various characters. For in one part the earth is oppressed by the sun in its course; in another part the earth is far removed from it; in another it is affected by it at a moderate distance".

It is unfortunate that even though a fine heritage existed in harmonizing architecture with climate, man lost sight of it, all of a sudden, and because of increased communication between nations borrowed one anothers 'styles' without properly considering their function or climatic suitability in the new position (Aronin, 1953). The developing countries, particularly in relation to their urban housing programmes, often failed to realize that the adoption of western technology and western patterns which had their origin in different socio-economic, cultural and climatic conditions can not provide answers to their particular needs. The resulting urban environment is very often climatically and socially inadequate.

Population explosion and increased urbanization have been two of the most distinctive features of many developing countries in the recent years. Even though in many developing countries the phenomenon of urbanization is more recent, the rate is alarmingly fast and it seems to be accelerating further. Apart from the problem of creating urban job opportunities for these teeming millions, the problem of providing shelters adequate at least from the view point of physical comfort and basic sanitation requirements is increasingly being considered a top priority in many national development schemes.

Like many developed countries such as Britain, Holland and Denmark, shortage of land is proving to be a very serious problem in many developing countries including Bangladesh. The high density of population and the absorption of food producing areas by urban expansion have become very critical factors indeed and the case for a high density living, specially in the urban areas, is only too obvious.

The question of density, however, is a complex one because its implications - physical, socio-economic and climatic - are far-reaching.

As has been pointed out by Rolf Jensen (1966, p.8), density expressed as a number of living units per acre is not by itself the sole qualitative measure of a housing development which also depends greatly on planning and amenity standards and livability of houses. There is also the quantitative assessment of density in terms of bulk of buildings, site coverage and any necessary height limitations as a means of securing socio-economically and climatically balanced built forms. In the context of Bangladesh, urban housing needs to strive primarily for physical comfort and health at low cost ensuring at the same time that housing density is commensurate with urbanization, the availability of land for urban use and the need for conservation of agricultural land.

Principles of climatic design are as valid in low cost developments as they are in expensive ones. In fact application of principles of climatic design to low cost developments is much more significant in the sense that unlike the wealthy elite, inhabitants of low cost dwellings cannot escape the consequences of poor design through mechanical air-conditioning. Also climatic design need not involve additional resources. On the contrary, design with climate can often result in significant cost reductions. In the light of the energy crisis throughout the world, the need for climatic design is being increasingly felt even in the affluent societies of the western world who hitherto could afford to ignore climate in relation to built form and rely heavily on mechanical means for control of the indoor environment.

Climatic control by natural means, however, has its limitations (Fig. 1). Victor Olgyay (1957) writes: 'We do not expect to solve the problems of uncomfortable conditions by natural means only. The environmental elements helping us have their limits. But it is expected that the architect should build the shelter in such a way as to bring out the best of the natural possibilities'. The degree of sophistication in environmental control is largely a socio-economic question (Lee, 1958). 'A value judgement will be involved in deciding what degree of comfort we want to achieve and how much we are prepared to pay for it' (Koenigsberger et al., 1974)

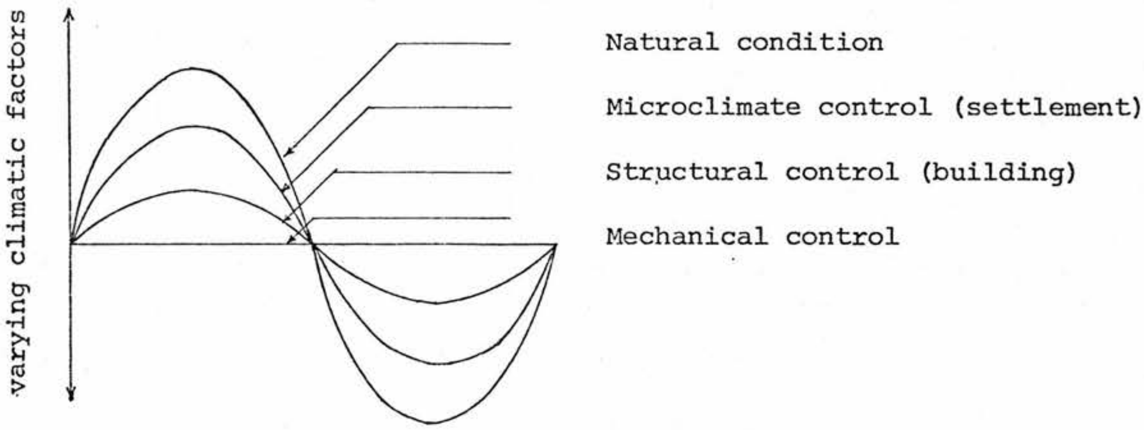


Fig. 1. Potential of climatic controls (Source: Koenigsberger et al., 1974, p.92)

The trial and error stage of climatic design is long past and the need for adopting the techniques of scientific analysis and reasoning has been increasingly realized through the last couple of decades or so. It has been evident that to meet the problem of climatic control in built forms in an orderly and systematic manner, a pooling of efforts by several sciences is required. The first step is to review the existing climatic conditions and this depends on the science of Meteorology. The next is to determine the comfort requirements and the answer for this lies in the field of physiology. The third step is to establish the form-performance relationships using

Physics and the engineering sciences. Finally the results are to be synthesized and adapted to architectural solutions. The current investigations follow this sequence, generally speaking.

To sum up, this thesis is an attempt to tackle the climatic aspects of a specific architectural problem in a specific socio-economic, cultural and geographic situation and under a specific climatic condition. Because of the intention of producing a comprehensive climatic design guide for the particular architectural problem we are concerned with in relation to the sun and the wind, it was necessary to incorporate a considerable degree of well known information in this volume. The thesis in this respect has some of the character of a design manual. Apart from the theoretical treatment of the principles of climatic design in relation to the given problem, experimental investigations in a wind tunnel were carried out in connection with ventilation studies in groups of 'porous' buildings. It is hoped that the approach and the methods adopted in carrying-out the investigations and analysis will be found simple, appropriate and comprehensive enough and the results and the forms in which they are presented will be found useful and convenient enough to be used in practice. Also the work may hopefully encourage further research in this area of climate-built form relationships, both in terms of the relationships themselves and in developing methodologies of formulating the knowledge in a design-orientated manner.

1.2 INTRODUCING DACCA, BANGLADESH

Bangladesh is situated between 88°10'E and 92°40'E longitudes and 20°40'N and 26°40'N latitudes. It comprises an area of 55,126 square miles. Dacca, the capital and premier city of Bangladesh is centrally located on the northern bank of the river Buriganga (Fig. 2).

1.2.1 Historical background:

Dacca is known to have been in existence since the 7th century A.D. At that time Dacca was under the Buddist Kingdom of Kamrup. From about the 9th century A.D., it was ruled by the Hindu Sen Kings of Bikrampur. Dacca of that time was identified as Bengalla and was probably a small town consisting of a few market places and a few localities of various craftsmen and businessmen. After the Hindu rulers, Dacca was under the Muslims for a long time - 1299 to 1608 - before the arrival of the Mughals. In the early 17th century, the Mughal control on Bengal was established and Islam Khan, the army commander, chose Dacca for his capital in 1608. He named it Jahangir Nagar after the name of the then emperor of India. For about a century Dacca remained the capital of Bengal and a centre of Mughal culture. During that period, with a population of one million, Dacca reached the peak of its past glory (Taifoor, 1952).

The 'Golden age' of Dacca ended when the capital of Bengal was shifted to Murshidabad in 1706. At the inception of British power around 1765, Dacca began to decline in importance and contract in size. Calcutta was growing in importance and it was difficult for Dacca to compete with Calcutta which, as the capital of British India, enjoyed the patronage of the rulers. The population came down to 200,000 in 1800 and with the destruction of the muslin industry (excellent hand-woven cotton fabric) in 1838, it decreased to 68,038 (Taylor, 1840,p.360).

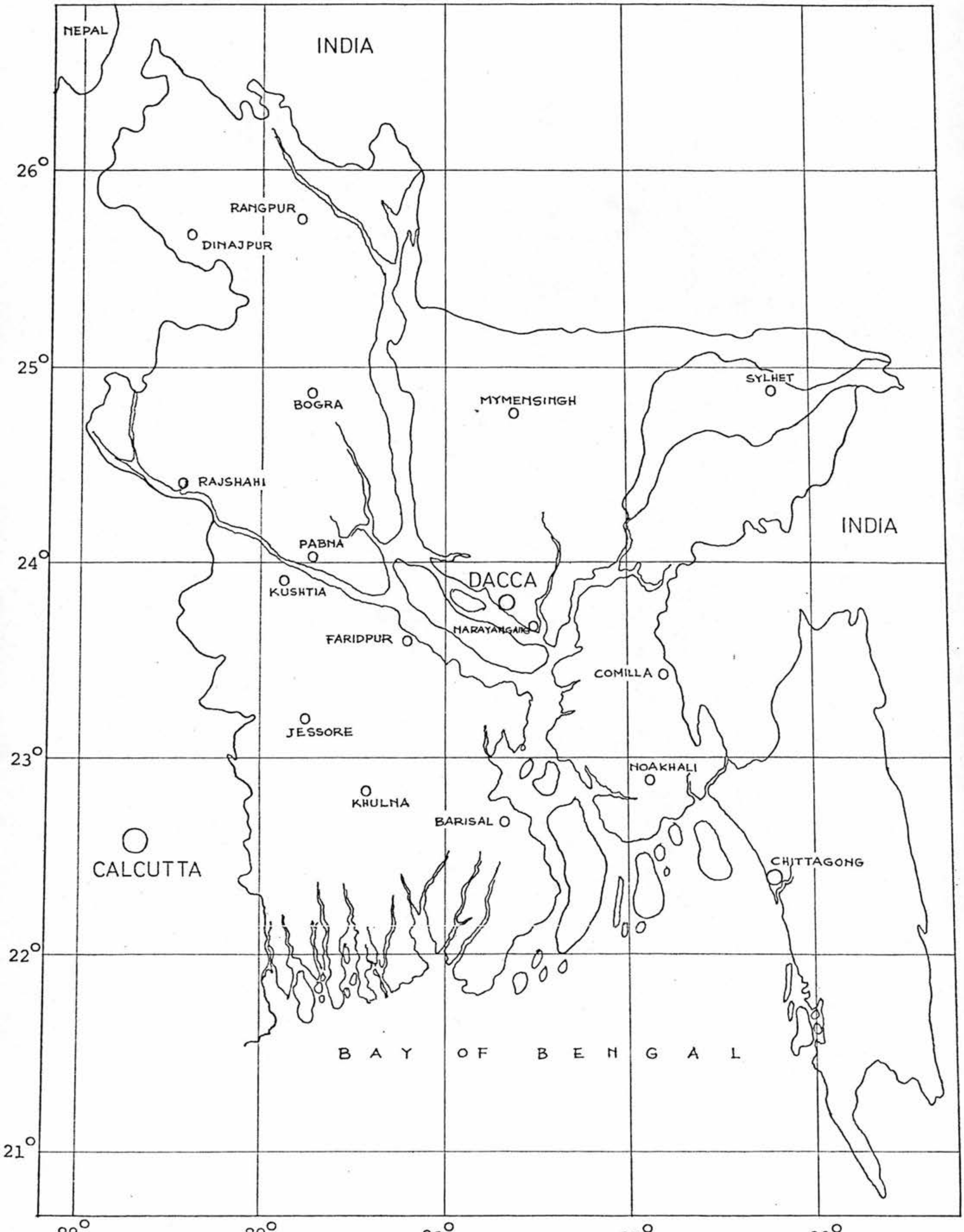


Fig. 2. General map of Bangladesh.

Dacca had another period of revival when it was made the capital of the newly created province of East Bengal and Assam in July 1905. During that period, the population began to rise again and it was 153,609 in 1911. A change in the government policy brought about the break-up of the province in 1912.

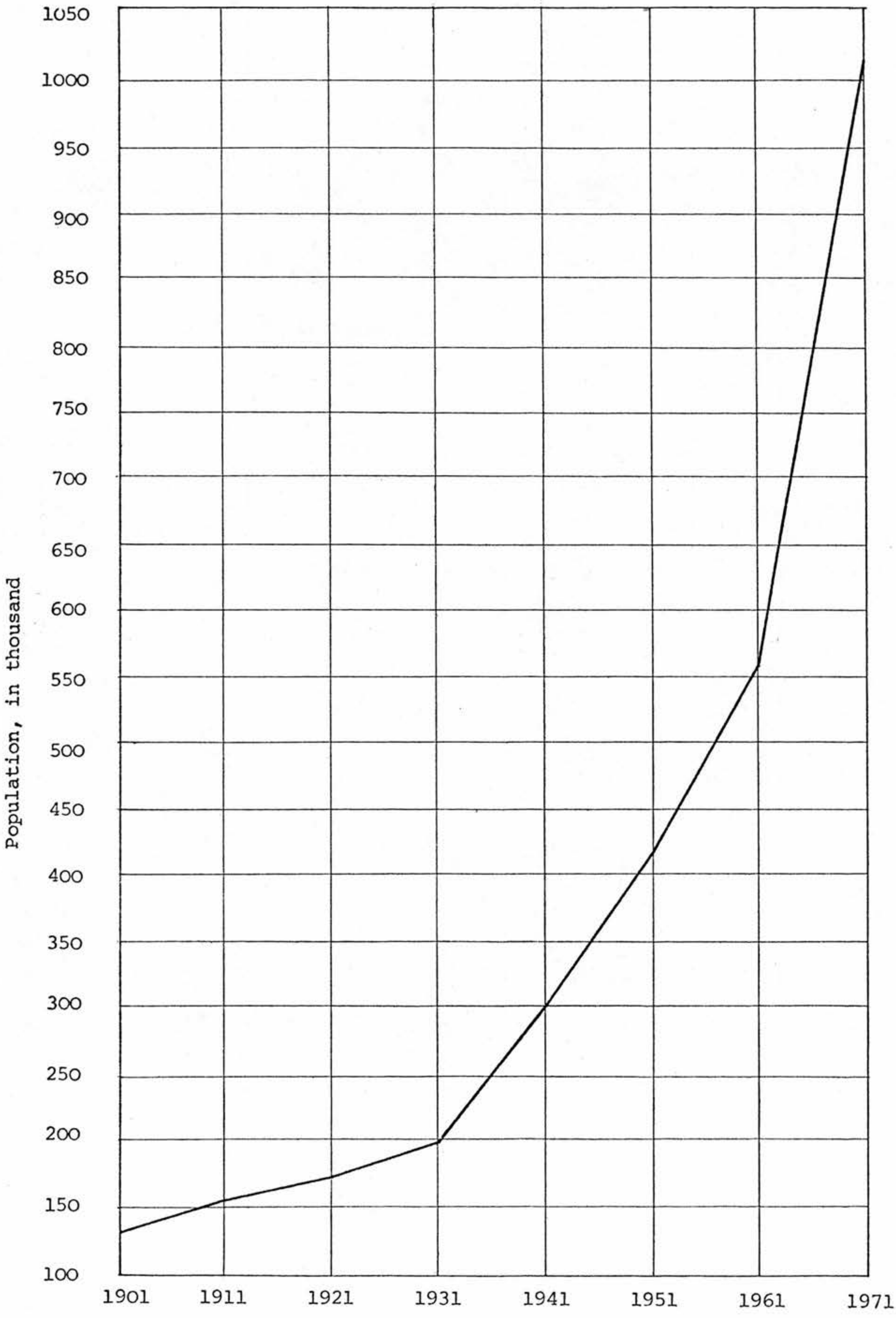
The third era of Dacca's growth began with the independence and partition of the Indian sub-continent in 1947 and the emergence of Pakistan with Dacca as the capital of its eastern province. Since then Dacca has been growing at a fast rate. The urban population of Dacca rose from 213,218 in 1941 to 276,033 in 1951 and exceeded 558,000 in 1961 (Fig. 3). With the emergence of Bangladesh as an independent country in 1971, Dacca has been called upon to shoulder even greater responsibilities as the seat of administration and the cultural centre of an independent country. Consequently pressure for the growth of urban Dacca has reached a new peak. The present urban population of Dacca is estimated to be over a million spread over an area of over 35 square miles.

1.2.2 The present housing scene in urban Dacca:

The present landscape of urban Dacca is a mosaic of ancient, mediaeval and modern growth. The urban Dacca of to-day consists of two distinct parts:

(i) The Old Dacca:

This is the area close to the river Buriganga existing and flourishing through different periods of the history of the city up till 1947 when independence and partition of the Indian sub-continent took place. The core of the area is immediately on the north bank of the river and grew through centuries since the pre-mughal days (Fig. 4).



<u>Fig. 3.</u> Growth of urban population of Dacca.
(Source: Urban Development Directorate, Dacca; Bangladesh census, 1973).

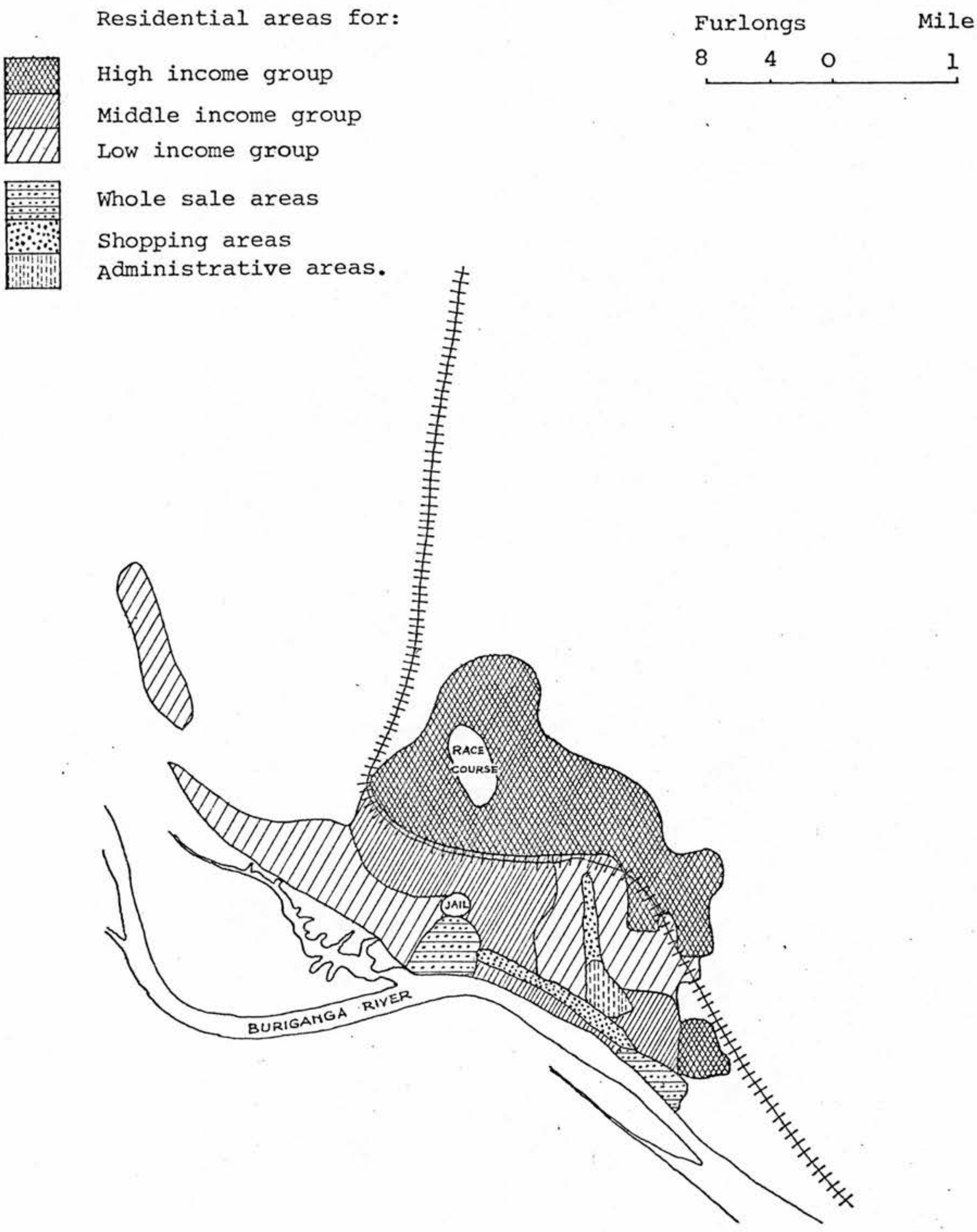


Fig. 4.

Dacca city landuse, 1947

(Source: Department of Geography, University of Dacca)

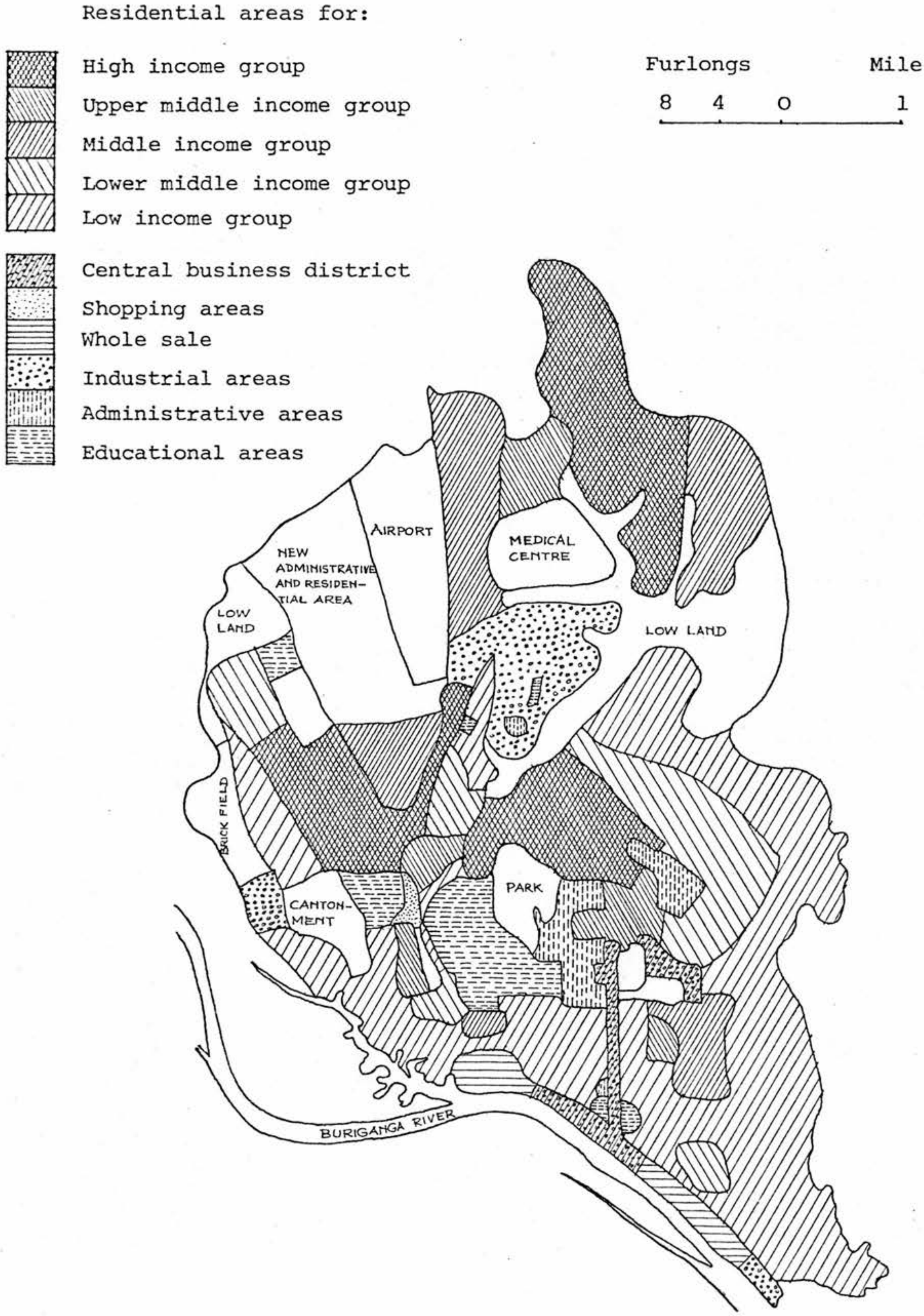


Fig. 5.

Dacca city landuse, 1970.

(Source: Department of Geography, University of Dacca).

(ii) The New Dacca:

This comprises the growth after 1947, primarily on the north of the Old Dacca (Fig. 5). Dacca is hemmed in by its river in the south and by side tracts of low lying land on the east and the west which is flooded annually up to a depth of about 8 feet during the monsoon months. Expansion is possible only in the north and hence the growth of the city is taking the shape of an elongated belt some 12 miles long with the old town as its broad base and its apex northward in the direction of Tongi. Two other prongs are in the direction of Mirpur on the north-west and Gulshan in the north-east.

The core of Old Dacca is a labyrinth of narrow streets and old brick buildings two to three storeys high with occasional medium rise modern building blocks here and there standing up as signs of patchy renewal efforts through the post-partition years. There is a large number of small scale workshops and service industry mixed with commercial premises and houses containing a large section of the population of the city. The old buildings reflect an alien culture (Mughal) with complete disregard for local climatic conditions such as the need for cross ventilation or the effect of heavy rainfall. From the climatic viewpoint, the quality of the built environment in this area has remained bad since the early days of its history with two and three storey brick buildings raising their heads above a cluster of meaner housing, narrow streets threaded with by-lanes and different localities or 'Mahallas' interconnected by feeder roads. The situation deteriorated further in the years immediately following the creation of Pakistan in 1947. The large influx of people from different parts of the country as well as from India into the city created, almost overnight, an unprecedented demand for housing. In those initial years, this demand was largely met by division of the existing houses and compounds, mainly in the old city, thereby increasing its population density and physical congestion which was already in a deplorable state.

The New Dacca on the other hand grew more or less in a planned manner under the control of various agencies, notably the Department of Communications and Buildings of the Government and the Dacca Improvement Trust. In the housing sector, the major efforts came from the government, semi-government and autonomous agencies and institutions who employ a large section of the urban population. The government policy in this respect consisted of two distinct approaches. Firstly, the high and the upper middle income groups of the population were encouraged in private house building by allotment of residential plots in planned residential neighbourhoods on government acquired land such as in Dhanmondi, Gulshan and Banani residential areas. Secondly, the government built several housing estates consisting of walk-up type apartment blocks, mostly for its own employee belonging to all income groups - the high, the medium and the low. The semi-government and autonomous agencies and institutions followed this second approach and built apartment housing for large proportions of their employees. Apart from these efforts, the wealthier sections of the community, notably the professionals and the businessmen provided a significant volume of the new housing stock, mostly detached and built on privately owned land. All these efforts, however, have been far too inadequate in terms of the existing and ever increasing urban housing demand and a vast majority of the urban population belonging mostly to medium and low income groups have been forced to live in the Old Dacca in extremely congested surroundings and in shanty town environments on the fringes of the New Dacca.

The government's allotment of generous residential plots for detached houses in the heart of the city such as in the Dhanmondi area as well as in the Gulshan and Banani areas, which will soon become a part of the central region of the Greater Dacca, has resulted in housing density pattern varying from less than 5 houses per acre to more than 50 houses per acre (Fig. 6). This density pattern is incompatible with the existing and the future urban housing need and the availability of land for urban use, not to speak of its undesirability from the socio-economic and climatic view points.

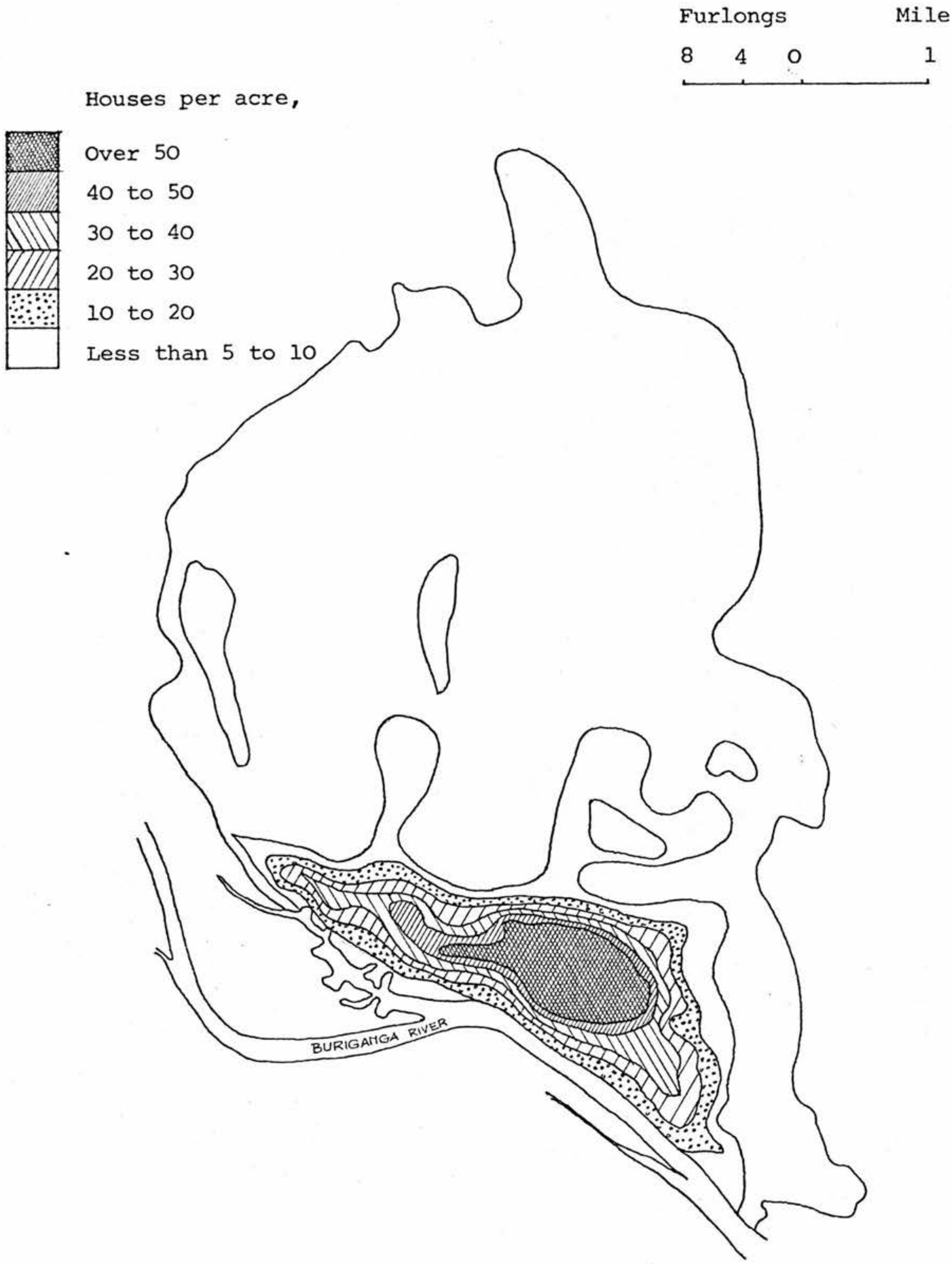
1.2.3 The future need:

It is now obvious that the policy and planning adopted in the creation of new housing stock in urban Dacca since its inception as the capital of the then East Pakistan has failed to meet the real need, namely provision of satisfactory housing for the vast majority of the urban population consisting of the middle and the low income groups. This failure can be attributed to many factors - lack of foresight in planning, lack of a sense of social justice, lack of national resources and so on.

Some aspects of the housing scene in urban Dacca can be highlighted as follows on the basis of the discussions so far:

(i) The Old Dacca, housing a large section of the urban population, is extensively blighted and in urgent need of renewal.

(ii) The supply of land for urban use is limited while the urban population is growing at a fast rate. This calls for extreme care in land utilization. The highest possible density pattern commensurate with the socio-economic and climatic



<u>Fig. 6.</u>

Density of houses

(Source: Department of Geography, University of Dacca).

requirements becomes an essential criterion for all future housing developments in urban Dacca.

(iii) Adequate resources need to be made available for launching a massive house building drive and sustaining it through the years to come within the framework of a sensible and practical development plan for urban Dacca.

(iv) The major initiative for tackling the housing problem in urban Dacca must come from the government because the private sector can neither handle the complexities involved nor can it master the necessary resources.

1.3 DESCRIPTION OF THE PROBLEM UNDERTAKEN FOR INVESTIGATIONS

From the preceding discussion, the following points emerge:

(i) As the capital and premier city of Bangladesh, urban Dacca will need large scale mass housing projects for its fast growing urban population over the years to come.

(ii) The shrinking land/man ratio in growing urban Dacca makes it extremely important to use maximum possible housing densities in all future mass housing developments. The densities need to be determined on the basis of the physical, socio-economic and climatic requirements.

(iii) The design and construction of the buildings should be such that cost per unit is reasonably low so that more units can be built with the resources that can be made available to the housing sector. This will invariably mean using primarily local materials and construction techniques in an efficient manner. The essential criteria of the form need to be physical comfort and health in the built environment at appropriate densities and at low costs. The design must make best use of natural means in securing comfort and sanitation in the built form.

(iv) Adequate awareness of the environmental implications for built forms is widely lacking. In the field of architecture, the concept of aesthetics borrowed from the so-called 'international style' reigns supreme resulting in awful misuse of scarce national resources and poor performance of the built forms. It is high time to put an end to such romantic pursuits of irrelevant concepts and adopt sensible and rational approaches to regional problems.

The research problem was conceived on this background scene of housing in urban Dacca and its future. The aims are two-fold: firstly, to formulate an approach for adequately and conveniently incorporating climatic considerations into the design decisions and secondly, to investigate and illustrate the form-performance relationships which can be used in the design process. Both of these are to be looked into from the viewpoint of securing human physical comfort in indoor spaces.

Because of the fact that the climatic forces are measurable and the relevant design criteria are quantifiable, it seems possible that the interactions between the forces and the form can be investigated objectively and that form-performance relationships can be used as convenient design aids - both in the evaluative and generative contexts. Designers are increasingly realizing the importance of designing with climate and it is hoped that this work will make some useful contribution in this area.

1.4 THE APPROACH TO THE PROBLEM

1.4.1 The approach rationale:

Man, climate and his dwelling form have been interdependent since the early days of human history. 'The concept of building as a filter between man and his environment does, most probably, account for the origin of buildings'(Hillier, 1970). Subsequently, with social and cultural developments, the role of buildings and built forms has vastly increased. Nowadays buildings and built forms are aimed at the realization of a number of social functions. In brief, buildings and built forms can be regarded as 'a climate modifier, a behaviour modifier, a cultural modifier and a resource modifier; the notion of modification containing both the functional and (ecological) displacement aspects' (Hillier et al, 1971).

History shows that the importance of regional and climatic approach to design was lost sight of for some time and it is not until the fifties that man once again began to realize the need for regional and climatic approach to design. Trial and error and intuitive methods were no longer satisfactory in the light of the urgency and complexities of modern requirements and scientific methods of investigations and reasoning were urgently called for. The result has been that scientific investigations have bloomed all over the world concerning buildings, built forms, people and nature with a view to helping architects design environmentally balanced structures.

At the beginning of these environmental research activities, the notion persisted that 'design was a problem solving activity involving quantifiable and non-quantifiable factors. Research should bring as many factors as possible within the domain of the quantifiable and progressively replace intuition and rules of thumb with knowledge and measurements' (Hillier et al., 1971). Accordingly, the 'building science' movement emerged and over a relatively short period of time produced an extensive volume of specialized knowledge and techniques for the better formulation and achievement of specifications. Because of the fragmented nature of this research, the results were isolated packages of information and not related to the building or the built form as an architectural entity. The architect was left with the job of finding ways of synthesizing and applying the results which, it seems, was the most difficult part of the whole endeavour and for which he was not traditionally equipped. The result was that an 'applicability gap' developed between research and design over the years.

To rectify this situation, a new approach to architectural research has been suggested (Hillier, Leaman, 1972). It has been stated that architectural research concerns both the 'software' - the articulation of need - and the 'hardware' - the physical form to meet the need. The key idea is that research problems are to be conceived * on the basis of the different functions a building performs, namely the functions of a climate modifier, a behaviour modifier, a cultural modifier and a resource modifier. "Each of these functions can be * conceived separately as a people-thing relationship and each, in contrast to research oriented towards the 'atom of environment' deals with a holistic set which constitute one way of looking at a design problem" (Hillier et al., 1971). It has been argued that the approach 'has an underlying coherence and consistency' and that it 'offers a satisfactory conceptual model for architectural research - a model which accepts none of the traditional basic distinctions between research, development and design, between physical and human sciences or even between theory and application (Hillier, Leaman, 1972).

It is this 'holistic approach' in relation to climate that is adopted in this work because it is obviously more realistic and holds greater promise for producing results to be useful in the design process. However, the current work had to be restricted in relation to the time period available for carrying it out and accordingly, it was decided that for the purpose of this thesis investigations would be carried out in relation to two of the more important climatic factors only, namely solar radiation and air movement.

1.4.2 Details of the approach:

The main aim of the research was to establish form-performance relationships in relation to a specified criterion, namely human physical comfort in indoor spaces. The work involved three main areas of enquiry - firstly, human physical comfort and comfort requirements; secondly, description of the form and the relevant performances of the form and their respective measures; and thirdly, investigations of the relationships between variations in the values of the measures of the performances of the form and variations in the values of the measures of the corresponding descriptors of the form.

The enquiry in the first area was aimed at understanding the concept of comfort and its physiological basis and the methods of defining the 'comfort zone' in a given climate. The results of the enquiry made it possible to evaluate the given climate in relation to comfort requirements and also to draw up performance specifications for the form in that context. The research in this area involved gathering, evaluating and interpreting information from publications of basic experimental results on the subject and analysis and discussions of these.

The second area of enquiry concerned, first of all, an appropriate description of the form. One way of describing a form can be by a set of 'descriptors', each one having an appropriate measure with a value or 'descriptive content' to it - as opposed to the elements of a form which denotes characteristic units forming parts of the form. The 'descriptors' of the form are therefore attributes of the elements of the form. Thus 'orientation' of a facade can be a 'descriptor' of the form and it can have an angular measure with respect to a specified direction. Each 'descriptor' of the form with a value of its measure is capable of conveying only a partial description of the form and it is clear that in order to have a holistic description of the form, it is required to have an adequate set of 'descriptors' with their 'descriptive contents'. The advantages of this way of describing a form is that the descriptions are highly analytical dealing with a large number of 'dimensions' of the form and the descriptive contents are objective in character. As a result the descriptions are highly communicable and useful in practice.

It is not difficult to realize at this stage that a problem does exist as far as the formulation of an adequate set of 'descriptors' of a form is concerned. Clearly, it calls for an '*a priori*' concept of the form in order to be able to formulate its 'descriptors'. This seems to be an undesirable position to adopt at the beginning of a systematic search for a suitable form, especially from the viewpoint of a form-generative approach. But there is nothing unrealistic or 'unscientific' about it, particularly when the built environment and its action systems are concerned. The argument that design proceeds by conjecture-analysis rather than by analysis-synthesis (Hillier et al., 1971) can be cited in this connection.

Thus on the basis of a general consideration of the physical, socio-economic and climatic factors, an outline of the possible form was drawn in fairly general terms. It was then through an analysis of the interactions between the form and the climatic elements in relation to human physical comfort in indoor spaces, that an appropriate set of performances of the form and a set of relevant descriptors of the form and their respective measures were formulated.

Following the formulation of the appropriate performances of the form, the relevant descriptors of the form and their respective measures, it was necessary to investigate the relationships between variations in the values of the measures of the performances of the form and variations in the values of the measures of the corresponding descriptors of the form. As far as solar radiation was concerned, these investigations were carried out on a theoretical basis. For air movement, apart from the theoretical investigations, experimental investigations with scale models in a wind tunnel were undertaken.

Once the form-performance relationships were established, a set of desirable values for the measures of the performances were formulated on the basis of an evaluation of the given climatic conditions in relation to the comfort requirements. The form-performance relationships were then used as design aids in establishing desirable values for the measures of the corresponding descriptors of the form.

PART 2

THE BASIC CONSIDERATIONS INVOLVED

2.1 REVIEW OF THE CLIMATE OF DACCA

2.1.1 A general description of the climate:

In general, the climate of the region can be described as tropical monsoon. The year can be divided into three distinct seasons - the Summer, the Monsoon (rainy) and the Winter.

The summer season begins in March and continues until May. The highest temperature may go over $35^{\circ}C$ but the diurnal temperature range is very small. The season is characterised by a period of violent thunderstorms called the Nor'westers. They begin generally in the middle of March and continue until the monsoon breaks in June. The time of occurance and the amount of the Nor'wester rainfall vary from year to year. The sky is relatively clear most of the time but heavy dark clouds precede the thunderstorms. Wind velocities are typically low but prevailing quite steadily from the south/south-east directions. Strong winds occur during the thunderstorms.

The rainy season begins with the advent of the Monsoon in June and lasts until October. Rain can be sudden, heavy and wind-borne. The rainiest months are June, July and August. During this period heavy downpours are frequent. The heavy rainfall causes abnormally large surface run-off. The amount of rainfall received during the monsoon season is more than 70 percent of the annual rainfall. During this period, the sky is generally overcast with heavy rain-clouds. The summer wind still prevails. The diurnal temperature range is even lower.

The winter season begins in the month of November and continues up to the end of February. The temperature can drop down to about $7^{\circ}C$ and the maximum temperature can be up to about $30^{\circ}C$. Rainfall in this period is very low. The sky is clear most of the time. The prevailing wind is from the North/North-east and the speed is low. The diurnal temperature range is slightly higher.

In summary, the climate of the region is warm-humid. The mean maximum temperature during the summer months varies usually between 29°C and 32°C. In the winter months, temperature may occasionally fall below 7°C or 8°C but the mean minimum temperature remains in the region of 12°C to 15°C throughout the winter months. Both the diurnal and the annual ranges of temperature are quite narrow varying between about 8°C and 12°C. The relative humidity remains high for most of the time at over 75 percent but it may vary between 60 and 85 percent. The prevailing wind speeds are low. Summer wind blows from the South/South-east and the winter wind from the North/North-east. Rainfall is torrential during the monsoon months. Annual rainfall can be as much as 2000 mm. During severe storms, rain may fall at the rate of 70 - 80 mm/hr. for short periods. Except for the winter months, the sky conditions are fairly cloudy.

2.1.2 Specific meteorological data on the climate:

Published meteorological data on the regional climate is scanty. Hourly values are not available. Therefore, monthly mean values together with maxima and minima have to suffice. The relevant data available are given overleaf (Tables 1 and 2):

Table 1

Temperature °C	J	F	M	A	M	J	J	A	S	O	N	D
Monthly Mean Maximum	25.85	26.69	28.08	29.75	30.86	32.25	30.58	28.91	28.36	27.80	26.69	25.29
Monthly Mean Minimum	12.79	15.57	18.35	21.68	23.35	25.29	25.29	24.19	23.91	21.13	17.24	14.18
Monthly Mean Range	13.06	11.12	9.73	8.07	7.51	6.96	5.29	4.72	4.45	6.67	9.45	11.11
Monthly Average	18.35	24.46	26.13	28.91	28.91	28.36	28.36	28.36	28.36	27.24	22.80	19.46

Table 2

	J	F	M	A	M	J	J	A	S	O	N	D
Monthly Mean Maximum*	80	76	76	78	79	86	87	87	84	80	78	82
Monthly Mean Minimum*	54	50	45	51	72	78	79	78	79	73	66	64
Monthly Average*	67	63	60.5	64.5	75.5	82	83	82.5	81.5	76.5	72	73
Rain-fall, mm.	15.24	25.4	38.1	134.62	223.52	342.9	294.64	347.98	228.6	127.0	25.4	00.0
Dir-ection **	N/N-E			S/S-E							N/N-E	
Speed**	1-2 m/sec.			2-4 m/sec.							1-2 m/sec.	

* Relative humidity %   ** Prevailing wind.

2.1.3 Limitations of the meteorological data in relation to building design:

Traditionally, weather services devote more attention to forecasts for aviation than to any other aspects of meteorology. In modern times, however, many interested disciplines depend on meteorological services for accurate information on weather and climate. National meteorological services attempt to present basic climatic data in a general way according to standard forms which attempt to satisfy most requirements. Unfortunately, the usual methods of presenting climatic data are inadequate from the point of view of the special needs of the building industry (van Deventer:).

In the environmental design of buildings, hourly values of the climatic elements for an average day per month are desirable. Speed and direction of wind flow are not only subject to seasonal variations but also to diurnal variations. The recurrence of high and low temperatures in conjunction with coincident wind speeds and directions on an hourly basis is important in this respect. But such elaborate data are usually not available and normally monthly mean values together with maxima and minima have to suffice.

The regional climatic data published by the meteorological services are not representative of all the 'nuances of climate' of the areas surrounding the stations. Moreover, certain data collecting procedures do not suit the purpose of building design. For example, wind observations are usually gathered from towers high above the built form or in open country undisturbed by terrain factors. Obviously, these values cannot be applied directly in building design and in order to derive full benefit from the data collected in this way, they have to be interpreted in terms of the very fine-textured fabric of climatic variations which occur even within very small distances. Observations at the site can be useful in this respect.

Regional climatic data as published by the Meteorological services are useful in making a preliminary assessment of the climate and may be sufficient to form the basis of preliminary designs. The final design must take into consideration the local variations or the 'site climate' because local deviations of the regional climatic parameters can be quite substantial as stated below (Koenigsberger et al., 1974, p.37):

> "Air temperature in a city can be 8 deg. C higher than in the surrounding countryside and a difference of 11 deg. C has been reported.
>
> Relative humidity is reduced by 5 to 10% due to quick run-off of rain water from paved areas, to the absence of vegetation and to higher temperature.
>
> Wind velocity can be reduced to less than half of that in the adjoining open country, but the funnelling effect along a closely built-up street or through gaps between tall slab blocks can more than double the velocity. Strong turbulences and eddies can also be set up at the leeward corners of obstructions."

Site climatic data, however, are very rarely available and often not feasible to investigate. In most cases summary of regional data may be used with only qualitative awareness regarding local deviations. For a large project in an urban centre, observations must ideally be gathered at the site in order to formulate a more accurate description of the local site climate.

On the basis of the work of Bedford et al. (1943), Thomas and Dick (1953) suggested that the effective wind speed could be taken as being:

(i) One-third of the free wind speed when considering the first few storeys of buildings in the central parts of towns.

(ii) Two-thirds of the free wind speed for buildings in suburban areas and for the middle storeys of buildings in the central parts of towns.

(iii) Equal to the free wind speed in areas where there is no wind screen and the upper storeys of tall buildings.

These values in no way can be regarded as final, but can only be used as a guide. Also power law wind velocity profiles for surfaces of different roughness can be used as reasonable approximations of the prevailing flow conditions.

2.2 HUMAN PHYSICAL COMFORT AND THE 'COMFORT ZONE'

2.2.1 The concept of comfort and its physiological basis:

"In latin, comfort meant aid or increase of strength. During the past two hundred years in English the word has changed its connotation to 'ease; freedom from pain or trouble; that which ministers to content'. As a concept relating to inhabited places comfort is an affective state, subjective and individual as appetite or fatigue. Many variables are integrated by the subject to be judged as comfort and everyone is his own authority on the matter" (Macfarlane, 1958). However, investigations of a statistical nature with an understanding of the underlying physiology and psychology may indicate the ranges of environmental circumstances under which a given population may feel comfortable, generally speaking.

The word comfort is usually applied to the entire environment consisting of the thermal, visual, auditory, olfactory and tactile aspects and it can be considered, for the sake of convenience, to be categorized as such. Of these categories of comfort, concern for thermal comfort is the most frequent and vital because without it, any definition of comfort is impossible. For the purpose of this thesis only thermal comfort is considered here in detail.

Thermal comfort has no simple definition. It is a subjective sensation and not an absolute value. A study of thermal comfort must include an understanding of the heat transfer basis of thermal comfort i.e. how the human body exchanges heat with his environment. In order to maintain thermal equilibrium, the human body must, in the long run, produce heat by metabolic process at the same rate as it loses to the surrounding. Some parts of the body, such as the brain, maintains a very constant temperature whereas other parts, such as the limbs, tolerate quite large changes in temperature. In hot surroundings sweat moistens the skin and its evaporation extracts heat from the body. Cold surroundings cause shivering increasing the rate of metabolic heat production needed to maintain the heat balance. In the zone between noticeable sweating and continual shivering, the body controls its temperature by altering the flow of blood to the body surface. As we begin to feel warm, the blood vessels in the limbs and the body surface enlarge allowing more warm blood to flow near the surface, thereby allowing more rapid heat escape from the body to the environment. The onset of sweating accompanies this process. As we gradually feel cooler, less blood flows to the limbs and the surface and they cool down, so losing less heat to the environment. This makes the feet and hands chilly and shivering soon starts. These changes in the blood flow may be regarded as changes in the thermal resistance of the body tissues from the core to the surface.

Along with the internal body temperature, one other important physiological factor is the skin temperature which lies in the range of approximately 92°F (33.3°C) to 96°F (35.5°C). Just before or during sweating, there is very little variation in skin temperatures over the body surface. In cold surroundings, wide differences in skin temperatures occur over the body surface. The pain threshold for skin is about 113°F (45°C); below 50°F (10°C), pain and numbness from the cold occur.

With the above somewhat simplified understanding of the heat exchange process between the human body and his environment, it is possible to describe the state of thermal comfort as one in which a minimum of physiological effort is needed to maintain the body temperature.

2.2.2 The 'Comfort zone' and methods of defining it:

The combined effect of all the climatic variables on thermal comfort is a complex matter and there are no absolute values. Only approximate ranges for variations of the factors can be laid down corresponding to the comfort sensation. This is made still more difficult by the fact that thermal requirements differ with individuals, types of clothing and nature of activity being carried on. Furthermore, it depends on sex and age. Women in general prefer a slightly higher temperature for comfort than men. Also persons over 40 years of age generally prefer slightly higher temperatures for comfort than men and women below their age. Acclimatization has been found to account for a preference for a temperature seventeen degrees (^{O}F) hotter than that accepted in cooler climates (Fry, Drew, 1964). The term comfort zone can thus be applied only to the range of conditions within which at least 80% of the people would feel comfortable (Koenigsberger et al., 1974).

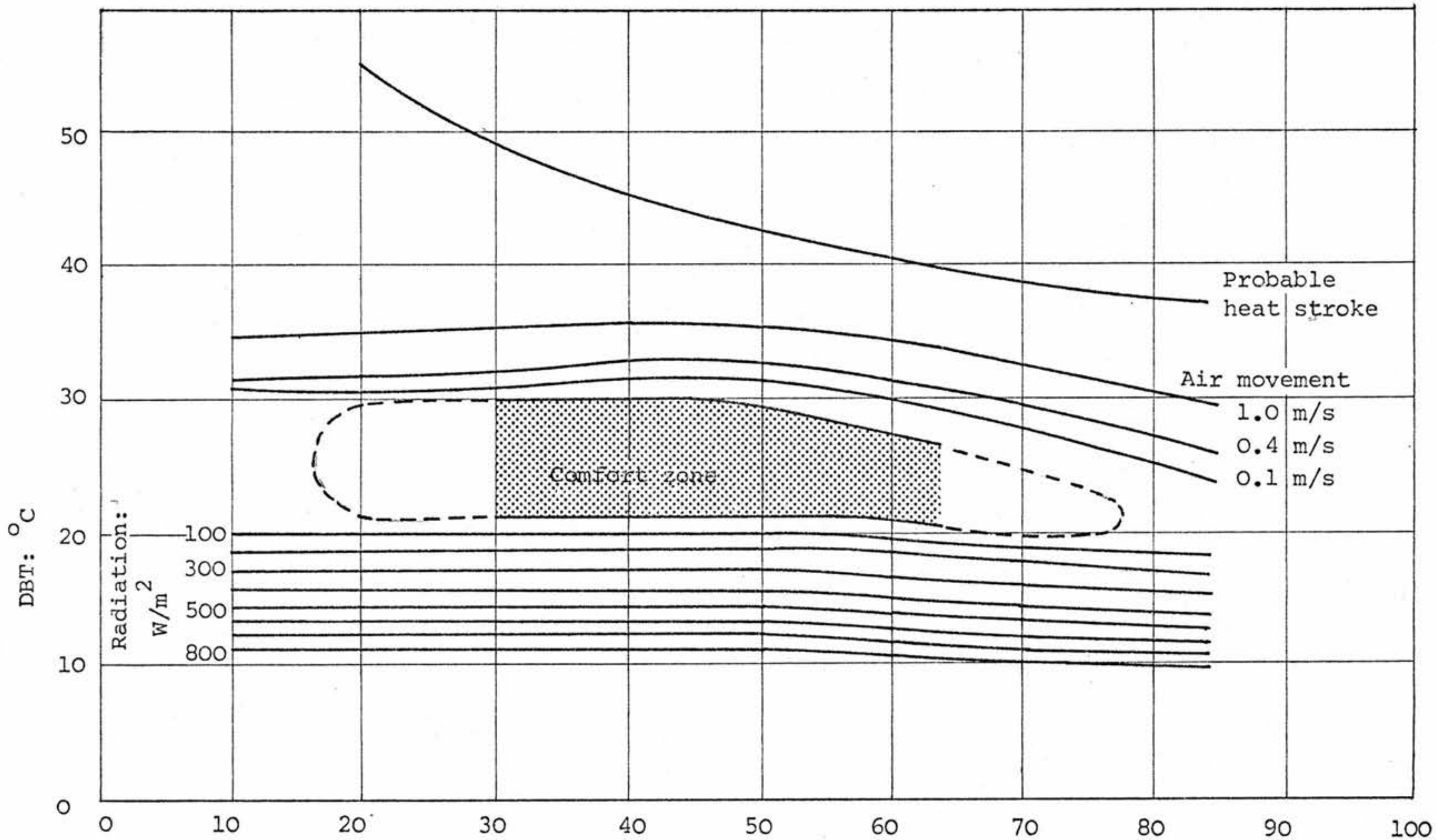
The problem of defining a comfort zone is not only one of determining the effects of various combinations of the affecting factors but also of conveniently expressing the affecting factors in terms of a single parameter. For example, many experiments have established temperature range for comfort in the equatorial region mainly between 72.5^{O}F (22.5^{O}C) and 85^{O}F (29.5^{O}C) at a relative humidity of 20-50%. This, however, does not take into account all the pertinant factors and does not express the findings in terms of a single figure.

Many attempts have been made to develop suitable methods for evaluation of the physiological and sensory effects of various combinations of the environmental factors and expressing them in terms of a single figure. These methods are usually referred to as thermal indices and appendix I gives a brief account of these. Victor Olgyay, on the other hand, arrived at the idea that since the four components, namely the air temperature, the relative humidity, the air velocity and the radiation, are each controllable by different means, there is no point in constructing a single figure index. Using published experimental data as a basis, he constructed a bio-climatic chart on which the comfort zone is defined in terms of DBT and RH, along with additional lines showing how the comfort zone is shifted up or down depending respectively on higher air movement and higher radiation (Olgyay, 1963). Olgyay's conclusions are generally regarded as being perfectly valid and because of the nature of the chart indicating not only the consequences of different combinations of the climatic factors but also the measures that may be taken to achieve a favourable condition, the chart appears to be the best suited in practice.

2.2.3 Defining the 'comfort zone' for Dacca:

The bio-climatic chart was originally developed for the inhabitants of the temperate zone of the United States, wearing customary clothing (about 1 clo), engaged in sedentary or light muscular work at elevations not exceeding 1000 feet (305 m) above sea level. However, the chart is applicable to other geographic regions with slight modifications in it. Olgyay (1963) writes: 'to apply the chart to climatic regions other than approximately 40^{o} latitude, the lower perimeter of the summer comfort line should be elevated about 3/4^{o}F for every 5^{o} latitude change towards the lower latitudes. The upper perimeter may be raised proportionately but not above 85^{o}F'. Revising some values of the original bio-climatic chart according to Australian CEBS findings, Koenigsberger _et al._ (1974) presented a modified chart for men at sedentary work, wearing 1 clo. clothing in warm climates in their Manual of Tropical Housing and Building, Part 1. Since the temperature limits of the comfort zone decrease by a mere 1^{o}F per 8^{o} increase in latitude, the chart can be conveniently used for the whole tropical region.

Thus, the 'comfort zone' for Dacca can be defined as indicated in the Figure 7. Explanation of the chart are as follows:



RH: %

<u>Fig. 7</u>

The bio-climatic chart

(Source: Koenigsberger <u>et al.</u>, 1974, p.51).

(i) The shaded area in the centre shows the outline of the comfort zone in still air.

(ii) Above this are the delimiting lines valid in each case for the air speed indicated. The lines indicate that in the higher temperature ranges, the comfort zone is extended by the corresponding increase in the movement of air.

(iii) Beneath are the delimiting lines for the addition of heat energy. These indicate that the comfort zone is correspondingly extended for low temperature ranges with the addition of radiative heat.

'The outline of the comfort zone should not be understood as fixed limits. The transitions are smooth and small deviations can, according to the use the building is put to, be accepted. These values can be maintained by artificial air-conditioning, whereas such precision can not be achieved by natural means' (Lippsmeier, 1969, p.86).

PART 3

LIMITATIONS ON THE POSSIBLE FORM

3.1 ADDITIONAL FACTORS DICTATING THE CHOICE OF THE FORM AND THE NATURE OF CONSTRAINTS IMPOSED.

Apart from the climate, two other factors dictating the choice of the form under the given conditions (discussed in Sections 1.2.2 and 1.2.3) are:

(i) The density requirements.

(ii) The resource limitations.

The Brahmaputra valley which includes Bangladesh is perhaps the most densely populated region in the world. The urban centres of the region are particularly worse off in this respect. It is absolutely imperative to strive for high densities in urban developments, particularly in urban housing. A high density in this context may perhaps best be defined as the one providing as many living units per acre as possible ensuring at the same time adequate or the best possible climatic advantages in relation to the sun and the wind.

Like most of the tropics, traditional housing in Bangladesh is rural housing developed in response to the need of a predominantly peasant population, drawing resources from the immediate surroundings. It is based on low investment and high maintenance. The traditional forms often represent sound solutions to climatic problems arrived at through ages of trials and errors.

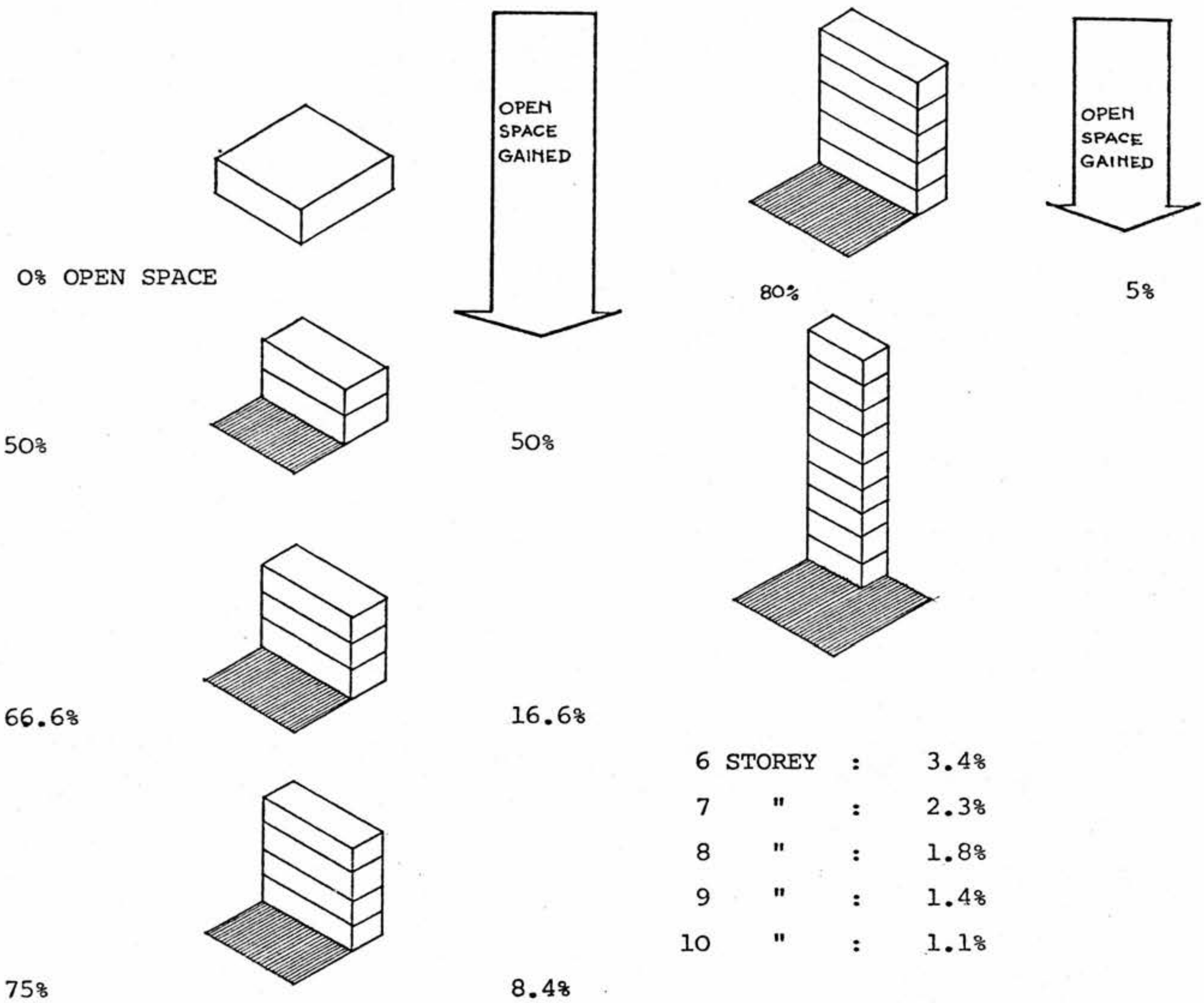
Yet the most pressing housing needs of the tropics are urban, and traditional forms, because of their origin in the life and economy of rural societies, are seldom suited to urban conditions. The scarcity of space and the life style and economy in an urban situation demands extreme care in planning as well as in the use of more durable materials and modern construction techniques in built forms. From the view point of the density requirement, a certain amount of vertical and horizontal grouping of units against one another seems unavoidable. In other words a flat type development is called for.

There are, however, other ways of achieving high densities but these are not suitable for a warm-humid climate. Richard MacCormac (1973), for example, has shown ways of achieving houses instead of flats at 250 pph. He showed the geometry of layout needed to give this density using terrace housing. In a warm-humid climate his layout, without the necessary concern for orientation, can not satisfy ventilation and solar radiation requirements.

In a warm-humid climate, adequate open spaces are absolutely necessary in built forms for achieving satisfactory air flow through buildings. For a given floor area, open space can be gained by making buildings higher. However, from 3-4 storeys and up, the extra open space gained per added storey becomes negligible as can be seen in the analysis presented in the figure 8. From the analysis, it is clear that sky-scrapers are not the answer to the quest for open-space.

The economic condition of Bangladesh is very difficult at present and it will demand proper harvesting and utilization of the scarce national resources over the years to come before any substantial improvement over the present situation can be hoped for. The housing sector along with the other sectors of national development must use limited available resources economically. This means cost per unit of housing must be kept reasonably low without jeopardizing the basic requirements of physical comfort, sanitation and safety.

~~Comparisons of cost as between single-storey and multi-storey dwellings are difficult to arrive at with all the factors taken into~~



<u>Fig. 8</u>

Open space gained with increase in storey height.

(Source: Blach: 1970)

[redacted].

Apart from the height control, the use of locally available materials and simple construction techniques can help in keeping the cost low. Brick and concrete are locally available and the technique of simple masonry construction is well practiced. The aspect that is lacking is the proper planning and design from the viewpoints of the physical, socio-economic and climatic requirements.

Thus, on the basis of an understanding of the constraints imposed by the factors discussed above as well as by the socially acceptable norms of building types and by the logic of construction, it seems possible as well as desirable, to draw at the outset a general outline of the possible form to be investigated in detail in relation to the climate - thereby limiting the number and range of variables involved within a practical and manageable range. The outline of the form concerning the investigations reported in this thesis were drawn as follows:

1. The geometry of the built form is to be defined by horizontal and vertical planes only, at right angles or parallel to one another.
2. The units are to be identical to one another.

3. Any variations in the configuration of the facades are to be brought about by advancing or receding one vertical strip in relation to another, each strip representing a set of identical spaces stacked vertically.
4. Openings in the envelope are to be located on two opposite walls of a unit, leaving the other ends solid for attachment to other units.
5. The overall development is to be in rows (not continuous but punctuated by gaps) of parallel blocks facing the favourable orientation in relation to the sun and the wind.
6. The buildings are to be primarily of simple masonry construction.

PART 4

FORMULATION OF A SET OF DESIRED PERFORMANCES OF THE FORM AND THEIR MEASURES, AND A SET OF CORRESPONDING DESCRIPTORS OF THE FORM AND THEIR MEASURES.

4.1 ANALYSIS OF THE INTERACTIONS BETWEEN THE CLIMATIC ELEMENTS AND THE BUILT FORM IN RELATION TO HUMAN PHYSICAL COMFORT IN AN INDOOR SPACE.

4.1.1 Solar radiation and the built form:

From the view point of the indoor thermal environment, solar radiation may be considered to interact with the built form in two main ways:-

(i) Direct solar irradiation into a space through an opening in the envelope of the form. This effects direct solar heat gain by the indoor materials including the furnitures with an eventual rise in the MRT of the indoor surfaces and in the indoor air temperature. This can be by far the greatest source of heat gain in an indoor space (Koenigsberger *et al.*, 1974, p.102).

(ii) Solar irradiation on the external surface of the envelope of the form. This causes heat gain by the materials of the envelope and a portion of this heat propagates through the materials inwards resulting eventually in a rise in the MRT of the indoor surfaces and in the indoor air temperature.

The effects on the indoor thermal environment due to direct solar irradiation into the space depend mainly on:-

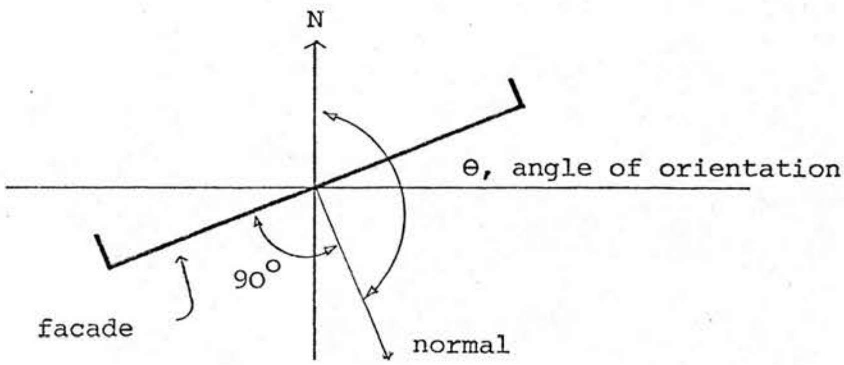
(i) Duration of solar irradiation into the space through an opening in the envelope of the form.

(ii) Intensity of solar irradiation on an appropriate reference plane, say, on the plane of the opening.

(iii) Width and depth (horizontally projected) of the beam of sunlight received in the space (i.e. the degree of coverage of the indoor space by the penetrated sun light).

These can be controlled respectively by:-

(i) Controlling the orientation of a facade (with inlet) in terms of the angle of orientation, i.e. the angle made by the normal to the facade with a reference direction, say, the N-direction. The facades, as stated earlier, are all vertical planes.



(ii) Controlling the orientation of the facade with opening.

(iii) Controlling the solid-void relationship on the facade in terms of the width and the height of the opening.

The thermal forces acting on the exterior surface of the envelope of the form are combinations of radiation and convective impacts. The effects on the indoor thermal environment due to solar irradiation on the external surface of the envelope will depend, as far as the fabric of the form is concerned, on the thermophysical properties of the materials and construction of the envelope. When solar radiation is incident on the external surface of the envelope, a part of the incident radiation is reflected and the remainder is absorbed into the material elevating its temperature. Part of this absorbed component is stored in the material to be dissipated to the surroundings later while the rest flows through the material to the cooler indoor surfaces and eventually to the indoor air. Thus the selective absorptivity and emissivity characteristics of the surface materials can form an effective defence against radiation impacts and the extent of solar heat infiltration into the space through the materials of the envelope is partly dependent on these characteristics of the surface of the envelope. Materials which reflect rather than absorb solar radiation and which more readily release the absorbed quantity as longwave thermal radiation will cause lower temperatures within the structure and hence lower heat gain by the indoor space.

The daily heat load variations on the external surface of the envelope of the form causes a corresponding oscillation inside the structure but there are two differences:-

(i) the inside cycle will be damped, i.e. there will be a decrease in the amplitude.

(ii) the inside cycle will lag behind the outside cycle, i.e. there will be a shift in phase.

Diurnal variations produce an approximately repetitive 24-hour cycle of increasing and decreasing temperatures. At the hot period during the day, heat flows from the environment into the building and at night during the cool period, the flow is reversed, i.e. from the building to the environment. The figure below (Fig. 9) shows the diurnal variations of external and internal temperatures in a periodic heat flow state. The two quantities characterizing this periodic change are the decrement factor (or amplitude attenuation, μ) and the time-lag (or the shift in phase, ϕ).

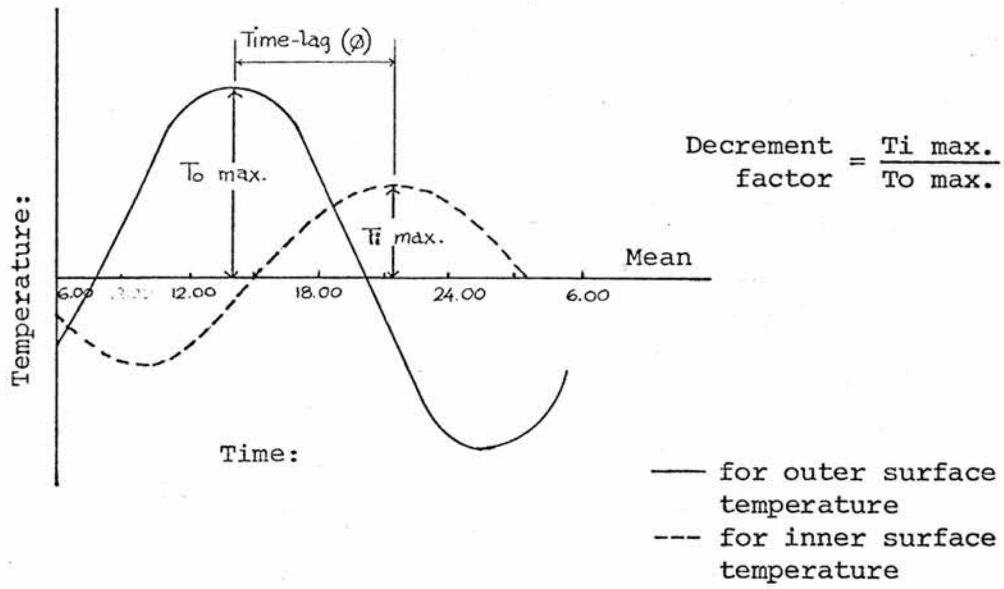


Fig. 9.

The first effect (i.e. the amplitude attenuation) is caused by the insulation value of the material of the envelope characterized by the U-value or the air to air transmittance, expressed in W/m^2 deg. C. The transmittance is a function of the thermal conductivity (or k-value in W/m deg. C), the thickness of the material employed in the construction (d, in m) and the surface conductances (f, in W/m^2 deg. C). The second effect depends on the heat storage value or the thermal capacity of the materials of the envelope characterized by the volumetric specific heat, ρxc - density times specific heat - expressed in J/m^3 deg. C. In other words, it can be said that the decrement factor and the time-lag are mainly functions of the thickness and density of the materials of the envelope.

Experiments in the Building Research Station, Haifa, showed that the relative thermal effect of insulation is greater as the insulation is thinner (Givoni, 1969, p.121). Also the location of the insulation layer relative to the high thermal capacity mass has significant effects on the time-lag and decrement factor. An internal location produces a shorter time lag but greater decrement factor while the reverse is the case for external location.

In a warm-humid climate where there is a small temperature difference between the inside and the outside as a result of open planning and cross ventilation, the heat flow will be small anyway and thermal insulation should not normally be a critical factor. However, since the heat gain situation with strong solar radiation is in fact controlled by the sol-air temperature value and not by the air temperature alone, insulation is very important in those parts of the envelope of the form which are most exposed to solar radiation contributing to the undesirable heat gain in the space. Good insulation will prevent the elevation of inner surface temperature above the air temperature.

The heat storage value or thermal capacity controls the rate of temperature change that is propagated through the material. The larger the thermal capacity, the slower is the rate of change. Under conditions with large diurnal temperature variations as in the hot-dry climate, the significance of thermal capacity is much greater than that of insulation. However, small diurnal variations as in the warm-humid climate do not help the buildings to cool off sufficiently at night to allow the storage of heat during the day. Under such a climate the principle of heat storage can not thus be effectively used.

Thus, we see that solar heat infiltration through the materials of the envelope of the form will depend on a large number of thermo-physical properties of the materials and construction of the envelope. These include the absorptivity (of solar radiation) and emissivity (of longwave radiation) of the surface materials, surface conductance and thermal conductivity, thickness and density and position of the insulating layers or cavities. It is possible to combine these factors and reduce them to three main variables which can be used to specify the thermal performance of a component of the form required under given conditions in a given climate. These variables are:-

(i) U-value - air to air transmittance, W/m^2 deg. C.

(ii) Solar heat gain factor - heat flow rate through the construction due to solar radiation, expressed as a fraction of the incident solar radiation. From the sol-air temperature equation $T_s = To + \frac{Ixa}{f_o}$ where, T_s = Sol-air temperature in ^oC, To = Outside air temperature in ^oC, I = radiation intensity in W/m^2, a = absorptivity of the surface and f_o = outside surface conductance in W/m^2 deg. C, we have, $T_s - To = \frac{Ixa}{f_o}$ Thus, the extra heat flow rate per unit area due to radiation is given by, $q = \frac{Ixa}{f_o} \times U$ (W/m^2) From this, the solar heat gain factor is given by: $\frac{q}{I} = \frac{a \times U}{f_o}$

(iii) Decrement factor & time-lag - The amplitude attenuation and the shift in phase respectively of the internal temperature cycle in relation to the external cycle.

From the discussion so far, it is clear that heat gain through the materials of the envelope of the form caused by solar irradiation on the external surface will depend on:-

(i) Duration of the solar irradiation received on the surface.

(ii) Intensity of solar irradiation received on the surface.

(iii) Area of the surface exposed to solar irradiation.

(iv) The extent of solar heat infiltration through the envelope expressed as a fraction of the incident solar radiation on its surface.

(v) The decrement factor and the time-lag characteristics of the envelope.

These can be controlled respectively by:-

(i) Controlling the orientation of the facade.

(ii) Controlling the orientation of the facade.

(iii) Controlling the orientation of the facade, its configuration characteristics in terms of the depth of staggering between two adjacent and parallel vertical strips of the facade and also controlling the built space-open space relationship in terms of spacing between the parallel rows of blocks, thereby controlling shadow casting by one strip over the other and by one row of blocks over the other.

(iv) Controlling the U-value of the envelope and the absorptivity and surface conductance of its surface.

(v) Controlling the thickness of the envelope and its density.

4.1.2 Air movement and the built form:

Air movement is of the utmost importance in relation to ventilation requirements in a warm-humid climate. Moving air counteracts the feeling of discomfort arising as a result of high air temperature and relative humidity by increasing convective heat loss and accelerating evaporative cooling. For comfort ventilation, the air velocity over the occupied space and not the rate of air change is the significant factor. There is no direct relationship between quantitative flow and velocity through buildings. For example, a turbulent flow at a low rate might yield higher average velocities over the occupied space of a room than a laminar flow at a higher rate but directed just below the ceiling (Givoni, 1969, p. 239). Also for the same flow rate a long narrow room with openings on the narrow walls will generate higher indoor velocity than when the openings are on the wide walls.

Air movement is generated by pressure differences. Similarly, air flow through a building is induced by the pressure gradient across it which in turn is caused by:-

(i) Wind forces.

(ii) Thermal forces.

Flow under wind forces:

When an airstream flows over some distance unhindered, it will be travelling parallel to the ground but will have a characteristic velocity profile with the speed of the flow increasing with height above the earth's surface. The variation depends primarily on the upwind surface roughness and for the earth's surface there can be infinite numbers of possibilities.

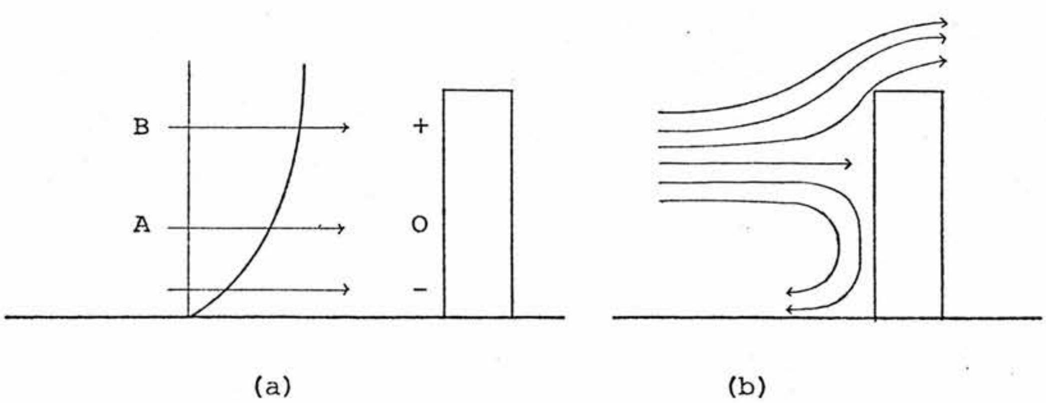


Fig. 10.

If such an airstream impinges on the face of a building, then from Bernoulli's equation $P + \frac{1}{2}\rho u^2 = Po$, it can be seen that the stagnation pressure or the total energy of the particle at A is less than that at B. There is thus a pressure gradient down the face of the building which causes the air to flow down the face of the building. At the same time the air near the top of the building finds it easier to curve up because of the lower pressures in the oncoming airstream above the building height. The point at which this division occurs obviously depends upon the details of the building and its surroundings but roughly its position will be about two-thirds of the height of the building from the ground. On the dividing stream line, the air flows side-ways along the front face of the building and separates at the edges. Away from the dividing streamline, the flow will be outwards and upwards or downwards, depending on whether the point is above or below the dividing streamline.

The separation of the airstream at the sharp front edges thus generate a wake of separated flow at the rear (Fig. 11). This is a zone of relatively low pressure - the wind shadow zone and the extent of this zone is affected by the length, depth and height of the building block as well as its orientation in relation to the prevailing direction of the flow. The shear along the edge of the wake induces a return flow in the centre. Speeds within the wakes are thus generally lower than those outside.

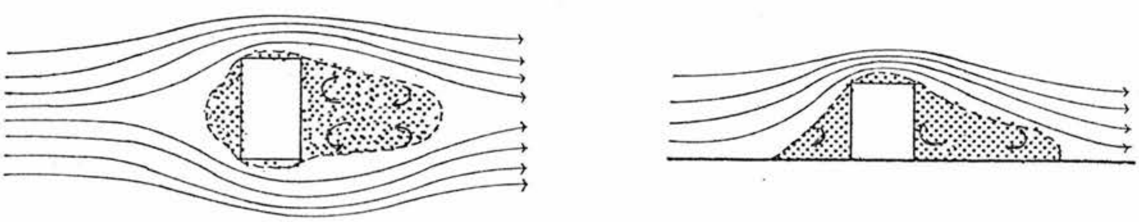


Fig. 11.

If there are other buildings asymmetrically placed in the wake, the division of the flow may move off the centre-line of the building as shown in the figure below (Fig. 12). Also if the flow is oblique to the building, there is no point where the flow is brought to rest and consequently vertical flow is not so pronounced. Higher velocities will be achieved on the faces with attached flow and the wake behind the building will be wider.

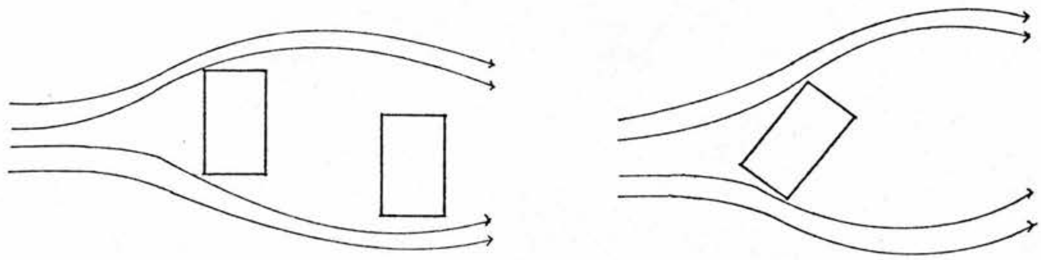


Fig. 12.

The corners of buildings may generate trapped vortexes. Also parallel rows of buildings may generate vortexes in the in-between spaces with consequent variations in air speeds and directions (Fig.13)

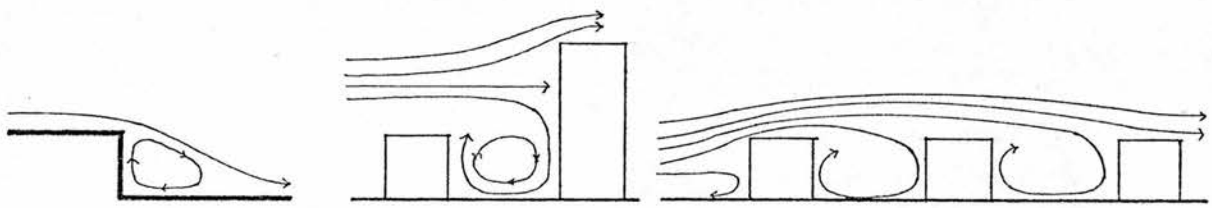


Fig. 13.

The pressure difference between any two points on the building envelope determines the potential driving force for ventilation through the building if openings were provided at these points. Sashes and louvers at the inlet can divert the air stream and because of the property of inertia, the air mass tends to maintain the deflected direction irrespective of the location of the outlet openings, (Caudill, Reed, 1952). Also the relative magnitudes of pressure build-up in front of the solid areas of the inlet facade, which in turn depends on the size and position of the inlet opening (apart from the nature of the flow), will govern the direction of the indoor air flow, again irrespective of the location of the outlet openings (Caudill, Reed, 1952). The average indoor air velocity will be affected by the direction of the flow at the inlet and by the relative sizes of the inlet and the outlet openings (Givoni, 1965).

In a turbulent flow, as can be found in a built-environment, the properties of the flow (velocity, pressure and so on) are constantly changing. The porosity of the building envelope further complicates the situation. All these make it extremely difficult to use pressure distribution as a means of pre-determining the indoor air flow characteristics.

Flow under thermal forces:

Thermal forces set up density differences between the indoor and the outdoor air. When the average indoor and outdoor temperatures are different, a difference is set up between their densities and the vertical pressure gradients differ correspondingly in and out of doors. Thus, the thermal force of ventilation depends on the product of the temperature difference between the indoor and the outdoor air and the height of the ventilation path. In residential buildings with 'open' planning, the temperature difference between the indoor and the outdoor air is small. Also in such buildings, the height of the ventilation path is normally very small. Thus, under such a condition, the contribution of thermal forces to indoor ventilation is not significant. However, in cold climates where temperature difference between the indoor and the outdoor air can be quite high, the contribution of the stack effect, particularly in multi-storey buildings, can be very significant.

From the discussion so far, it is clear that in a warm-humid climate, the comfort ventilation in an indoor space will depend on:-

(i) Average velocity of the airstream in the occupied space.

(ii) Degree of coverage of the occupied space by the indoor air stream.

These can be controlled respectively by:-

(i) (a) Controlling the geometry of the built form in terms of the length, depth and height of the blocks as well as grouping patterns of the blocks and spacing between them.

(b) Controlling the positions and sizes of the openings in terms of the height of location of the openings and the height and width of the openings themselves.

(ii) Controlling the openings with canopies, sashes and louvres.

4.1.3 Tabulated summary of the analysis:

Table: 1

THE CLIMATIC ELEMENT UNDER CONSIDERATION: Solar radiation
THE RELEVANT RESULT OF INTERACTION WITH THE FORM : Change in the indoor thermal environment.
THE RELEVANT PERFORMANCES OF THE FORM: 1. Direct solar heat gain by the indoor space as a result of receipt of solar radiation in the space through openings in the envelope of the form. 2. Indirect solar heat gain by the indoor space as a result of solar heat entry on the surface of the envelope and the subsequent flow of a part of the heat through the materials into the indoor space.

Table: 1 (Continued)

THE APPROPRIATE MEASURES OF THE PERFORMANCES OF THE FORM:
1.1 Duration of solar radiation received in an indoor space through an opening in the envelope of the form.
1.2 Intensity of solar radiation received on the plane of the opening.
1.3 Width and depth (horizontally projected) of the beam of sunlight received in the space.
2.1 Duration of solar radiation received on the surface.
2.2 Intensity of solar radiation received on the surface.
2.3 Area of the surface exposed to solar radiation.
2.4 The extent of solar heat infiltration through the envelope expressed as a fraction of the incident solar radiation on its surface.
2.5 The decrement factor and the time-lag produced by the envelope.
THE CORRESPONDING DESCRIPTORS OF THE FORM:
1.1 Orientation of the facade with opening.
1.2 Orientation of the plane of the opening (i.e. same as 1.1)
1.3 Solid/void relationships on the facade with opening.
2.1 Orientation of the facade.
2.2 Orientation of the facade.
2.31 Orientation of the facade.
2.32 Configuration of the facade.
2.33 Built space/open space relationships

Table: 1 (Continued)

2.41	Air to air transmittance of the envelope.
2.42	Solar radiation absorptivity of the surface of the envelope
2.43	Surface conductance of the envelope.
2.51	The thickness of the envelope (d).
2.52	Volumetric specific heat of the envelope (ρc)
2.53	Thermal conductivity of the envelope (k).
THE APPROPRIATE MEASURES OF THE DESCRIPTORS OF THE FORM:	
1.1	Angle made by the normal to the facade with the N-direction measured clockwise from it.
1.2	Same as above.
1.3	Height and width of the opening in relation to the dimensions of the facade, and its angle of orientation.
2.1	Angle made by the normal to the facade with the N-direction measured clockwise from it.
2.2	Same as above.
2.31	Same as above.
2.32	Depth of staggering between two adjacent and parallel vertical strips of the same facade.
2.33	Spacing between two successive parallel rows of blocks.
2.41	U-value of the envelope.
2.42	Ratio of the solar energy absorbed to the total energy incident on the surface.
2.43	Rate of heat flow through a unit area of the surface in W/m^2 deg. C.

Table 1 (Continued)

2.51	Thickness in metres.
2.52	Volumetric specific heat in J/m^3 deg. C.
2.53	Thermal conductivity in W/m deg. C.

Table: 2

THE CLIMATIC ELEMENT UNDER CONSIDERATION: Air Movement
THE RELEVANT RESULT OF INTERACTION WITH THE FORM: Comfort Ventilation in the indoor space
THE RELEVANT PERFORMANCES OF THE FORM: 1. Intaking of the prevailing wind through the inlets. 2. Allowing flow of the incoming air through the occupied space and out the exit openings.
THE APPROPRIATE MEASURES OF THE PERFORMANCES OF THE FORM: 1. Average velocity of the incoming air at the inlet. 2. Degree of coverage of the occupied space by the indoor air stream.
THE CORRESPONDING DESCRIPTORS OF THE FORM: 1. Geometry and grouping pattern of the built form. 2. Controlling features at the inlet (canopies, sashes and louvres)
APPROPRIATE MEASURES OF THE DESCRIPTORS OF THE FORM: 1. Length, depth and height of the blocks, their grouping pattern and spacing between the blocks. 2. Geometric details of the protective features (nature of construction, angle of inclination, and so on).

PART 5

THE FORM-PERFORMANCE RELATIONSHIPS

5.1 THE CLIMATIC ELEMENT UNDER CONSIDERATION: SOLAR RADIATION

5.1.1 General Considerations:

The sun's path across the sky-vault follows a definite traverse in relation to time of the year. At any given date and time, therefore, the position of the sun on the sky-vault in relation to a geographic location is precisely predictable. This means that the insolation and shading effects on buildings can be accurately predicted if 'clear-sky' conditions are assumed.

During cloudy days, the ratio of diffuse to direct radiation may be 1.00 (100 per cent), while during clear days it may be only 0.15. However, the overall heat received on a cloudy day (diffuse radiation, primarily) is much less than the overall radiation (direct plus diffuse) on a clear day. From design point of view, therefore clear sky condition may be assumed whenever necessary in investigating the sun-built form relationships.

Various techniques can be used for investigating the sun-built form relationships. These can be broadly classified as follows:

(i) Statistical approach using tabulated data and mathematical models.

(ii) Graphic systems using the sun-path diagrams and the associated protractors.

(iii) The system of model measurements using sun-dial and sun-machine instruments.

(iv) Computer simulations which may or may not include statistical factors.

The statistical approach is laborious and time-consuming if manual calculations are involved. It is, however, possible to develop computer programmes to speed up calculations. But even then a rapid appraisal of the solutions to a number of situations at the early design stage of a building will depend on whether the data generated by the computer is presented in the form of some kind of simple design aids for easy assimilation by the architect. Computer methods, generally speaking, tend to be either very specific, only dealing with narrow sub-problems, or, if more comprehensive, they tend to remain at the level of broad generalisation (Koenigsberger et al, 1974, p.273).

The graphic systems have the advantages that they are comprehensive and easy to use. The sun-path diagrams are maps of the sky-vault projected on a horizontal plane. There are several different systems of projecting the imaginary sky-vault with the sun-paths on a plane (Appendix III). In the equidistant projection method, the altitude angles appear on the diagram equally spaced. This assures equal readability for high or low angles and makes plotting easy. Sharma and Rao of the Central Building Research Institute, Roorkee, India prepared composite solar chart (sun-path diagram) covering the Indian sub-continent. The sun-path diagram for Dacca used in the current work was derived from this composite solar chart (Fig. 14).

The shadow angle protractor (Fig. 15) consists of two series of lines marked on a transparent semicircle which has the same diameter as the sun-path diagram. The first series of lines are curved and show the vertical shadow angles. The second series of lines which radiate out from the centre show the horizontal shadow angles. The diameter of the protractor is called the base line. The curved lines represent a number of hypothetical sun-paths. If the sun were to follow these paths, it would always appear to have the same altitude when seen in section perpendicular to the base line. The angle of the sun seen in section is the vertical shadow angle. It is measured from the horizon (0) up to the zenith (90). It should be noted that the sun's vertical shadow angle is equal to the solar altitude only when the sun's rays are perpendicular to the base line.

The solar radiation protractor for vertical surfaces (Fig. 16) used in this work was taken from Sharma and Rao's work. This was based on data on the Indian sky and was accepted as a close approximation of the Dacca sky situation. The base line of the protractor represents the surface orientation. The radiation intensity is shown by equiradiation contours - solid lines for direct and broken lines for diffused. The diffuse radiation is always present (during day time) whether the sun is directly shining on the surface or not and depends on the position of the sun on the sky-vault. For those hours when the sun is not shining on the wall, i.e. when the sun position is not within the protractor semicircle, the diffused radiation depends on the solar altitude alone. It can then be read as the value given by the intersection of the solar altitude circle with the line designated as the 'vertical surface'.

For investigating the sun-built form relationships, it is necessary to specify the days of the year and the times of the days with reference to which insolation and shading effects are to be investigated. From the view point of thermal design of built forms in the region we are concerned with, it was considered sufficient to use the two extreme days of summer and winter solstices, namely June 22 and December 22 respectively and the equinox, i.e. March 21 or September 23 as was suggested by Sharma and Rao. Also it was thought convenient and

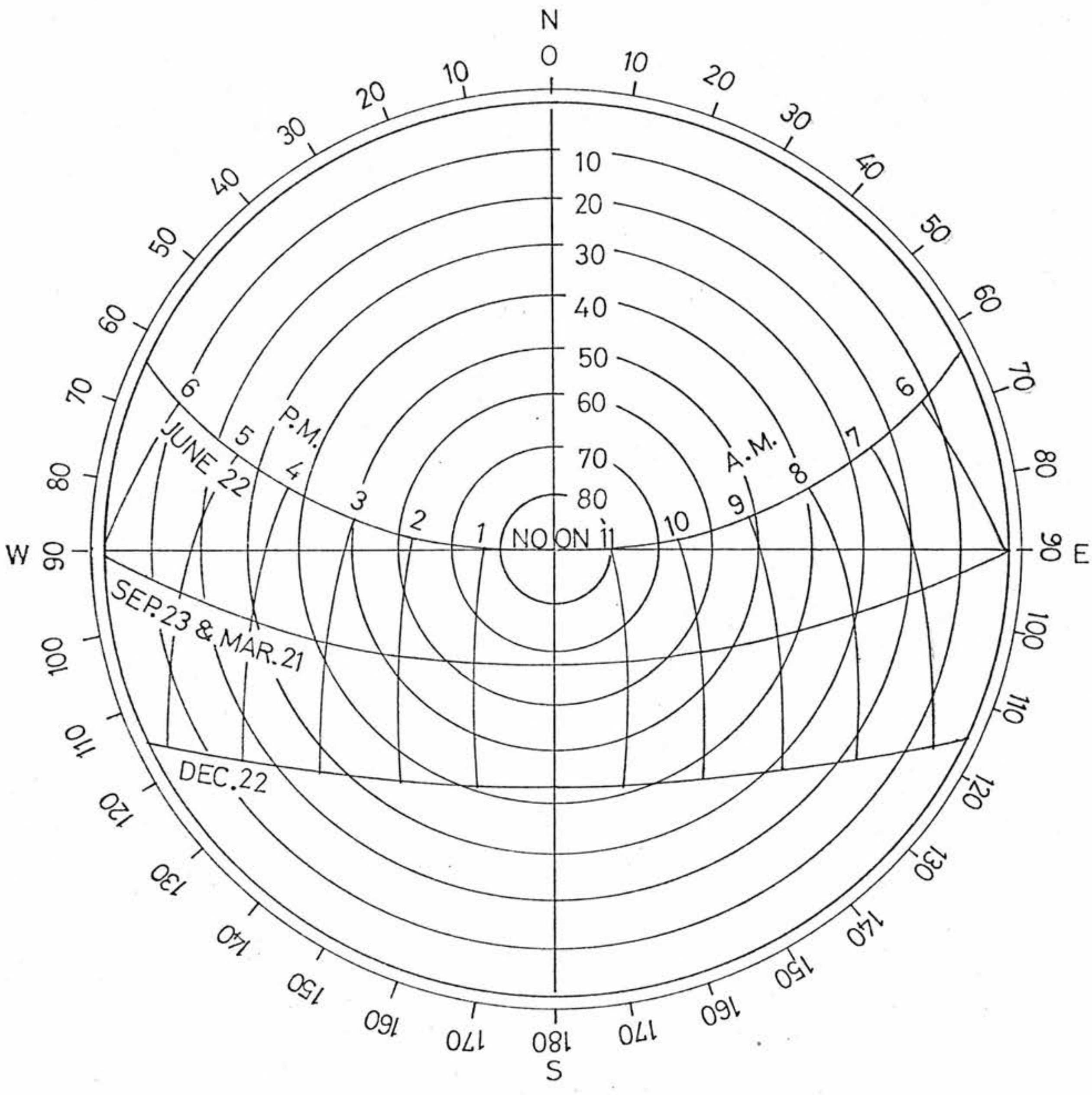


Fig. 14.

Sun-path diagram for 24°N latitude

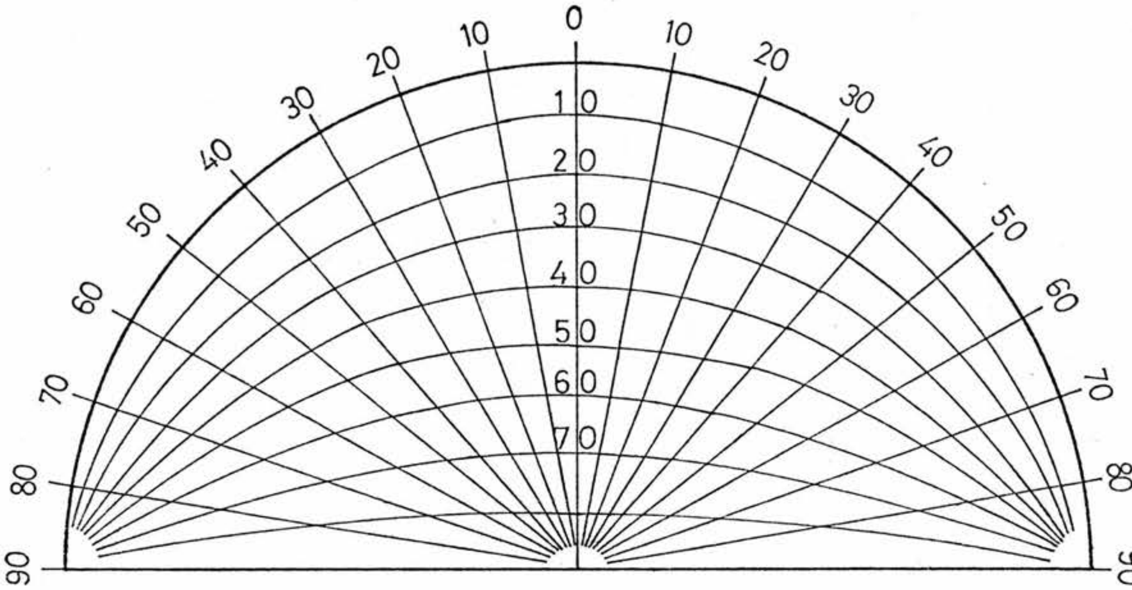


Fig. 15.

Shadow angle protractor

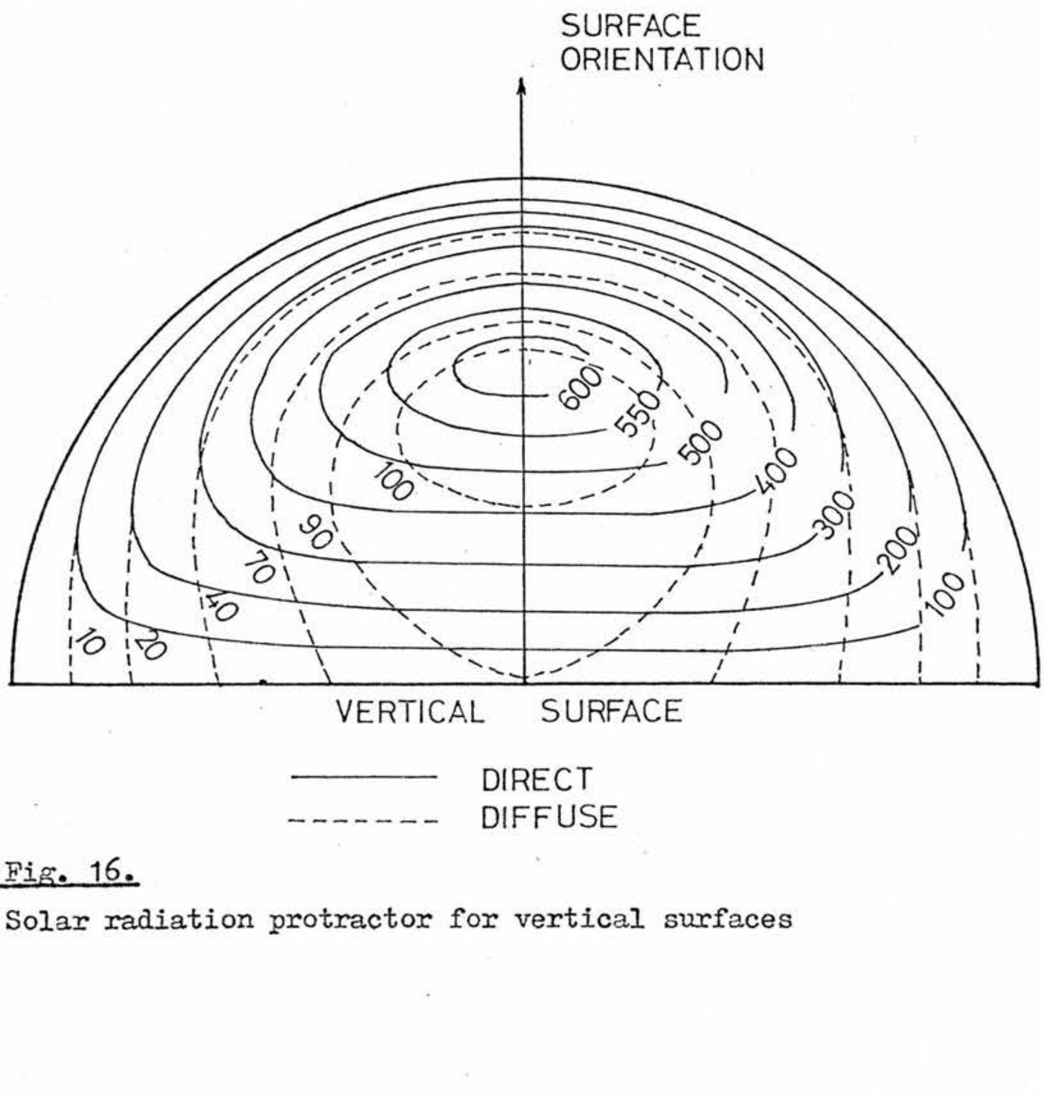


Fig. 16.

Solar radiation protractor for vertical surfaces appropriate to refer the solar data to the three instants of the days, namely the mid-morning (8.30 a.m. in summer, 9.15 a.m. in winter), the mid-day (12 noon) and the mid-afternoon (3.30 p.m. in summer and 2.45 p.m. in winter).

5.1.2 Enumeration of the desired relationships :

(i) Effects on the duration of solar radiation received on the surface of a facade due to variations in the angle of orientation of the facade.

(ii) Effects on the intensity of solar radiation received on the surface of a facade due to variations in the angle of orientation of the facade.

(iii) Effects on the degree of coverage of the indoor space by the penetrated beam of sunlight (i.e. on the width and the horizontally projected depth of the beam of sunlight in the indoor space) due to variations in the width and height of the opening and the angle of orientation of the facade with the opening.

(iv) Effects on the degree of exposure of a facade (in terms of the surface area) to solar irradiation due to variations in the spacing between successive parallelrows and due to variations in the depth of staggering between two adjacent and parallel vertical strips of the same facade and its angle of orientation.

(v) Effects on the extent of solar heat infiltration through the envelope (expressed as a fraction of the incident solar radiation on the surface) due to variations in the U-value of the envelope and the solar radiation absorptivity (a) and surface conductance (f_o) of the outside surface of the envelope.

(vi) Effects on the decrement factor and time-lag produced by the envelope due to variations in the thickness of the envelope, the nature of its construction and its density.

5.1.3 Investigating the relationships:

(i) Effects on the duration of solar irradiation received on the surface of a facade due to variations in the angle of orientation of the facade.

This relationship is investigated by using the sun-path diagram for Dacca and the shadow angle protractor. The protractor is placed on the sun-path diagram with the centre of the base line coinciding with the centre of the sun-path diagram and the 'surface orientation' line set in the direction of orientation of the plane (Fig. 17). The duration of solar radiation received on the facade is given by the uninterrupted length of the sun-path or the intersected portion of the sun-path between the base line of the protractor and the eastern or the western periphery of the diagram and 'above' the base line of the protractor. The results are tabulated as in Table 3.

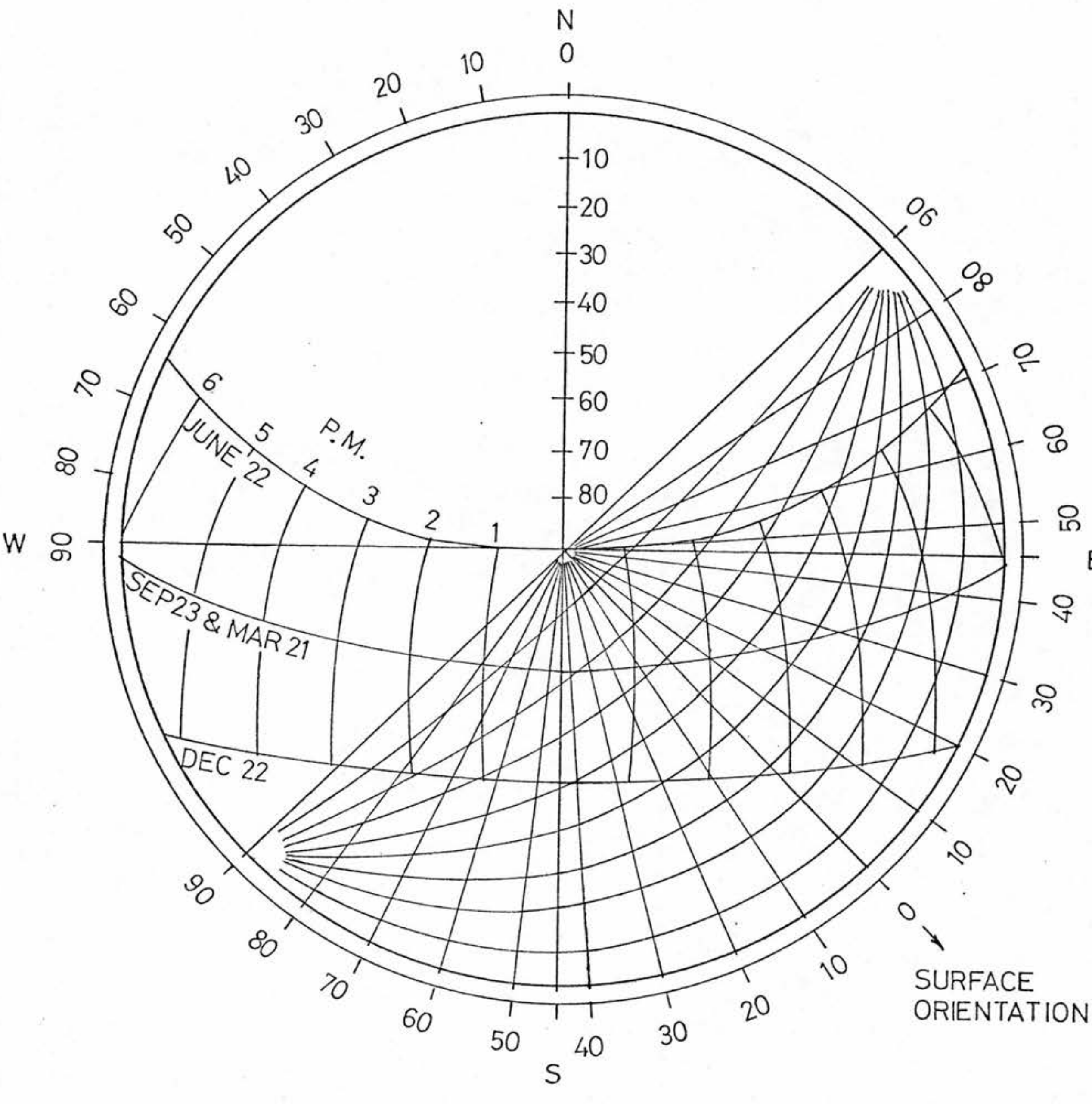
(ii) Effects on the intensity of solar irradiation received on the surface of a facade due to variations in the angle of orientation of the facade.

This relationship is investigated by using the sun-path diagram for Dacca and the 'total solar radiation protractor' for vertical surfaces. The protractor is placed on the sun-path diagram with the centre of the base line coinciding with the centre of the sun-path diagram and the 'surface orientation' line set in the direction of orientation of the plane (Fig. 19). The values of the direct and diffused components of solar radiation on the plane at the required instants of the days are read from the points on the direct and the diffused equiradiation contours on the protractor corresponding to the location of the sun on the sun-paths on the required days and at the required times. The results are tabulated in Table 4.

Table: 3

Angle of Orientation of the facade. (Clockwise from the N-direction).	Duration of solar irradiation received on the facade on:		
	June 22	Sep.23 & Mar.21	Dec.22
0^{o}	Sunrise to sunset	-	-
45^{o}	Sunrise to 12 noon	Sunrise to 10.30 a.m.	Sunrise to 9 a.m.
90^{o}	Sunrise to 12 noon	Sunrise to 12 noon	Sunrise to 12 noon
135^{o}	Sunrise to 12 noon	Sunrise to 1.25 p.m.	Sunrise to 2.50 p.m.
180^{o}	-	Sunrise to sunset	Sunrise to sunset
225^{o}	12 noon to sunset	10.30 a.m. to sunset	9 a.m. to sunset
270^{o}	12 noon to sunset	12 noon to sunset	12 noon to sunset
315^{o}	12 noon to sunset	1.25 p.m. to sunset	2.50 p.m. to sunset
360^{o}	Sunrise to sunset	-	-

The tabulated data can be expressed in graphic forms as in the Figure 18.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P.M.
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4
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JUNE 22
SEP23 & MAR 21
DEC 22
E
SURFACE
ORIENTATION
S

Fig. 17.

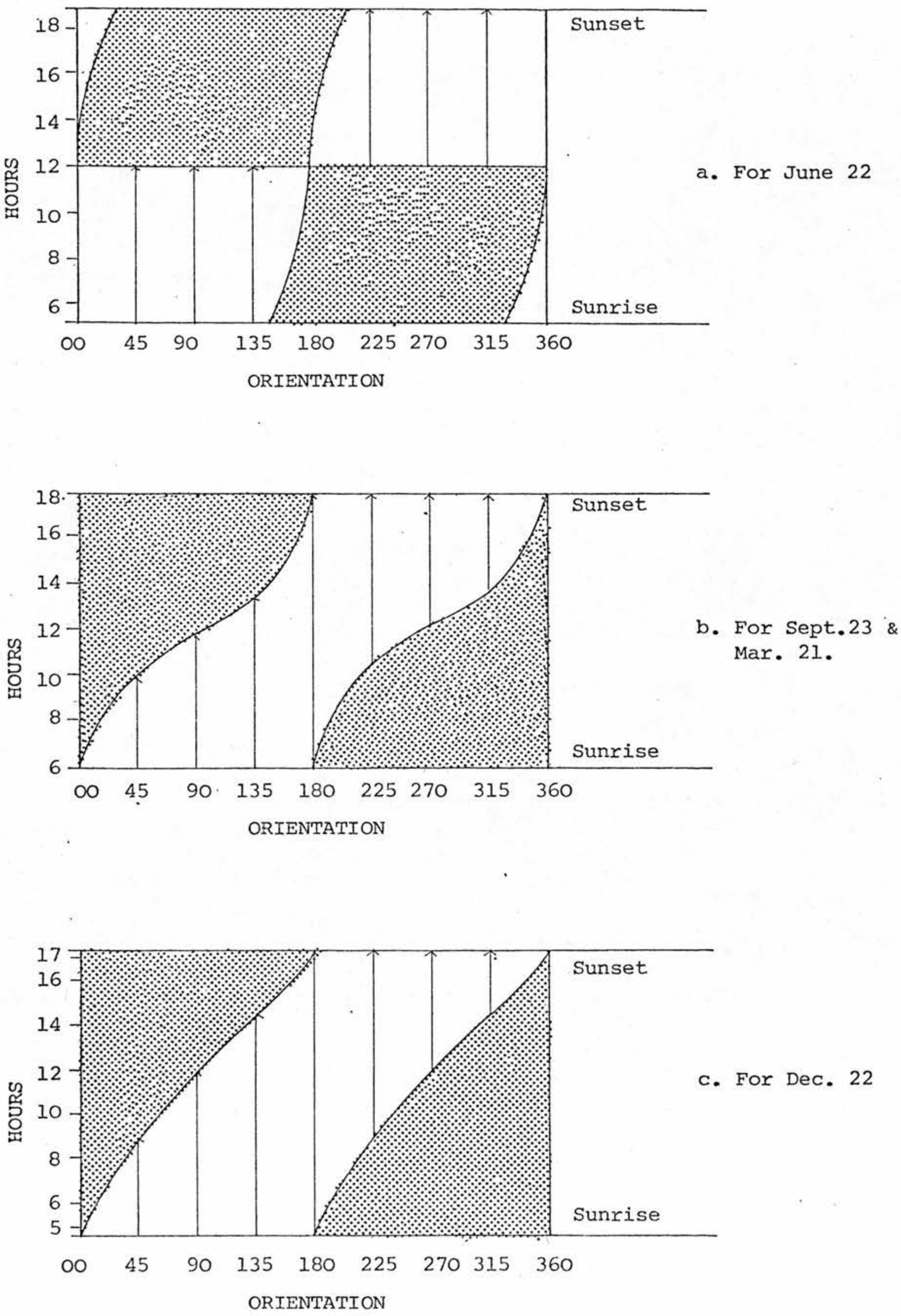
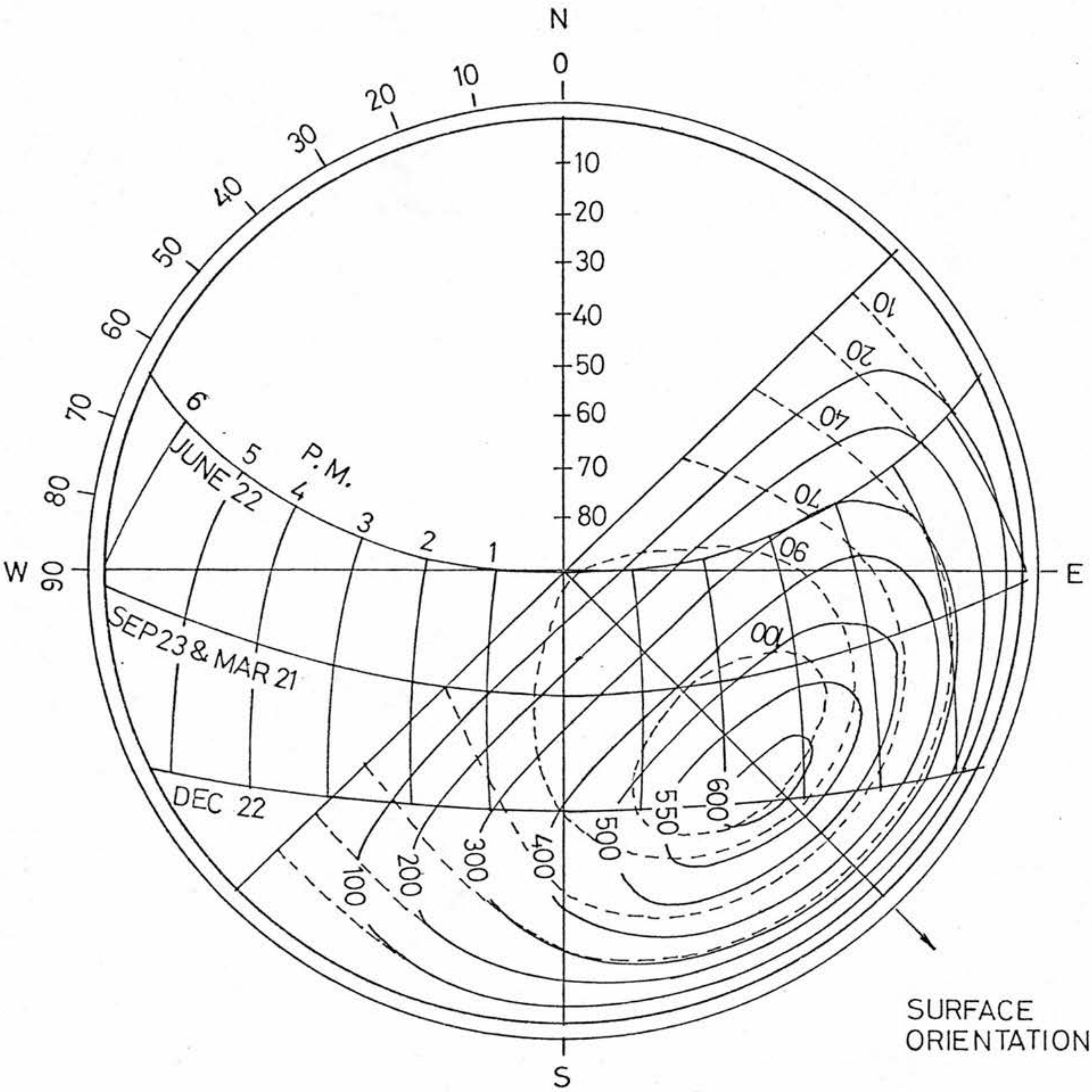


Fig. 18

Variation in the duration of solar radiation received on a facade due to variation in its angle of orientation.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P.M.
JUNE 22
SEP 23 & MAR 21
DEC 22
10
20
40
70
90
100
100
200
300
400
500
550
600
SURFACE ORIENTATION

Fig. 19

Table: 4

The Day	Orientation (deg.)	Radiation received at the instants: Mid-morning W/m^2			Mid-day W/m^2			Mid-afternoon W/m^2		
		Direct	Diffuse	Total	Direct	Diffuse	Total	Direct	Diffuse	Total
June 22	00	100	55	155	00	90	90	100	55	155
	45	500	95	595	00	90	90	00	50	50
	90	550	100	650	00	90	90	00	50	50
	135	325	80	405	00	90	90	00	50	50
	180	00	50	50	00	90	90	00	50	50
	225	00	50	50	00	90	90	325	80	405
	270	00	50	50	00	90	90	550	100	650
	315	00	50	50	00	90	90	500	95	595
Sep. 23 & Mar. 21	00	00	50	50	00	80	80	00	50	50
	45	250	70	320	00	80	80	00	50	50
	90	550	100	650	00	80	80	00	50	50
	135	550	100	650	250	95	345	00	50	50
	180	250	70	320	320	95	415	250	70	320
	225	00	50	50	250	95	345	550	100	650
	270	00	50	50	00	80	80	550	100	650
	315	00	50	50	00	80	80	250	70	320
Dec. 22	00	00	30	30	00	50	50	00	30	30
	45	00	30	30	00	50	50	00	30	30
	90	400	70	470	00	50	50	00	30	30
	135	600	100	700	400	90	490	00	30	30
	180	450	70	520	575	100	675	450	70	520
	225	00	30	30	400	90	490	600	100	700
	270	00	30	30	00	50	50	400	70	470
	315	00	30	30	00	50	50	00	30	30

The tabulated data can be expressed in graphic forms as in the Figure 20.

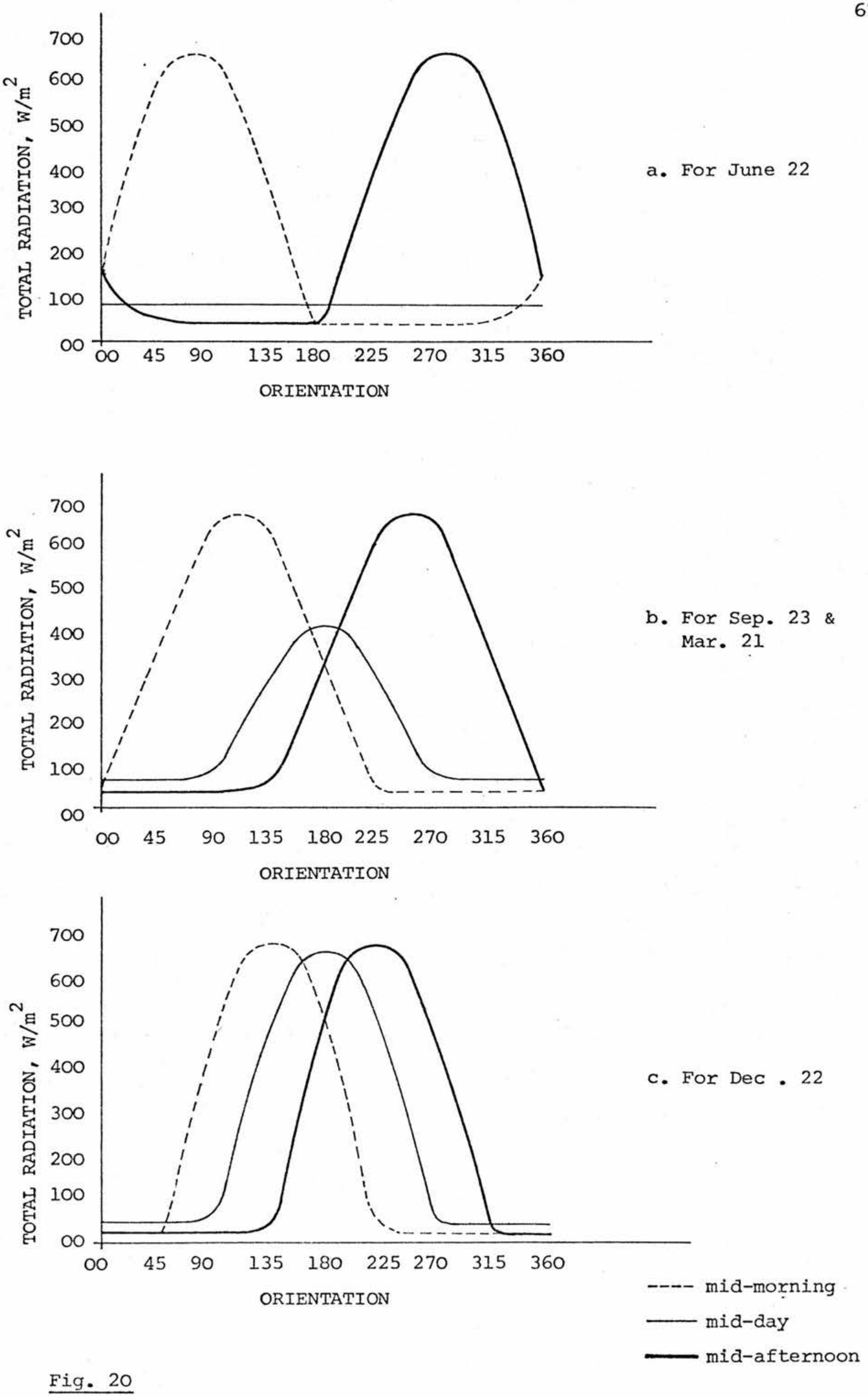


Fig. 20

Variation of the intensity of solar radiation (Total) received on a facade due to variation in its angle of orientation.

(iii) Effects on the degree of coverage of the indoor space by the penetrated beam of sunlight (i.e. the width and the horizontally projected depth of the beam of sunlight in the indoor space) due to variations in the width and height of the opening and the angle of orientation of the facade with opening.

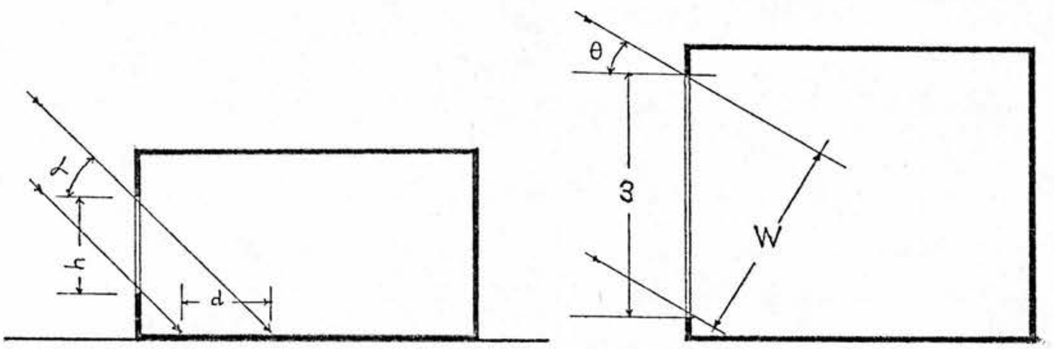
This relationship is investigated as follows:

Let h be the height of the opening on the facade,

w be the width of the opening on the facade,

d be the depth (horizontally projected) of the penetrated beam of sunlight,

W be the width of the penetrated beam of sunlight.



Section

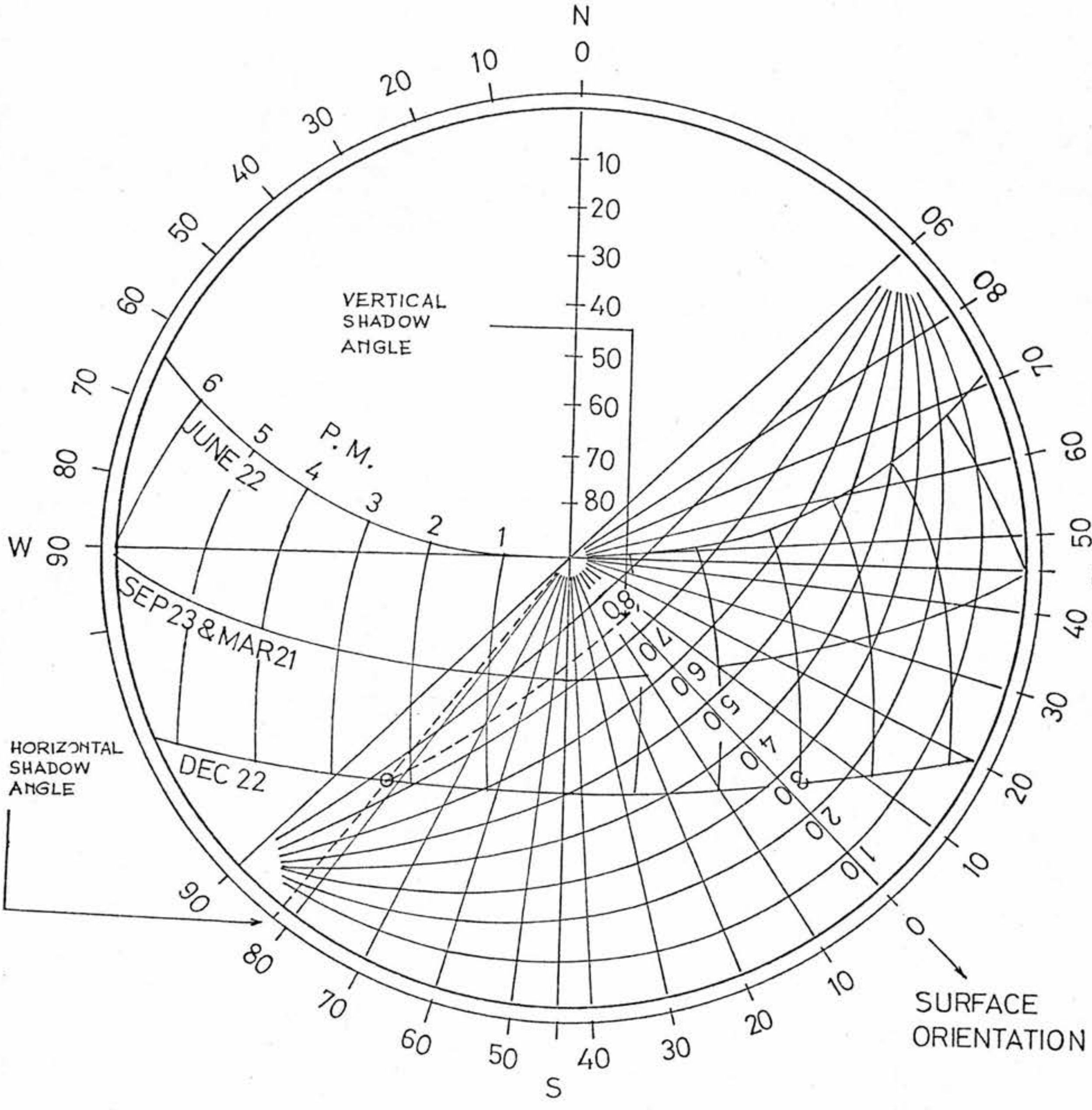
Plan

Fig. 21.

Then, from Figure 21, $d = h \cot \alpha$ where α is the vertical shadow angle with respect to the plane of the opening; and $W = w \cos \theta$ where θ is the horizontal shadow angle with respect to the plane of the opening.

Values of α and θ will be different at different instants of the days and for different orientations of the facade. Therefore, values of α and θ and also of $\cot \alpha$ and $\cos \theta$ need to be computed in relation to variations in the orientation of the facade. This can be done by using the sun-path diagram and the shadow angle protractor. The protractor is placed on the sun-path diagram with the centre of the base line coinciding with the centre of the diagram and the surface orientation line set in the direction of orientation of the plane of the facade (Fig. 22). The radial lines of the shadow angle protractor indicate the horizontal shadow angles on the required dates and at the required instants and these angles are read from the protractor scale. The curved lines of the protractor give the vertical shadow angles. The results are tabulated as in the Table 5.

Using the values of $\cos \theta$ and $\cot \alpha$ from Table 5 in the equations $W = w \cos \theta$ and $d = h \cot \alpha$, the width and the depth (horizontally projected) of the penetrated beam of sunlight in the indoor space can be computed and the results can be expressed graphically as in Figures 23a and 23b.


N
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VERTICAL
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HORIZONTAL
SHADOW
ANGLE
P.M.
JUNE 22
SEP 23 & MAR 21
DEC 22
SURFACE
ORIENTATION

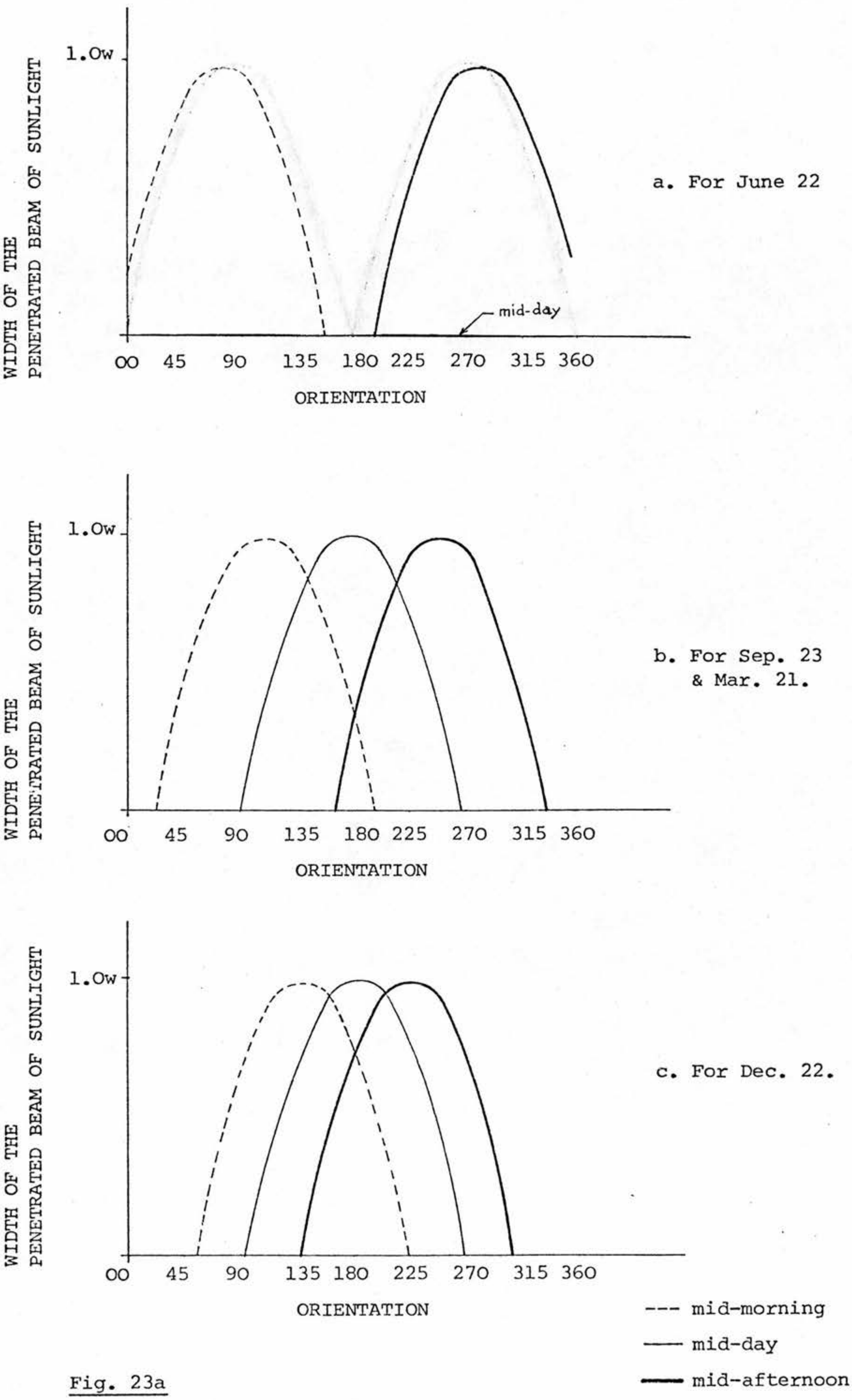
Fig. 22

Table 5.

The day	Orientation (deg)	Instants of the day											
		Mid-morning				Mid-day				Mid-afternoon			
		θ	α	Cosθ	Cotα	θ	α	Cosθ	Cotα	θ	α	Cosθ	Cotα
June 22	00	77^{+}	74	0.23	0.29					77^{-}	74	0.23	0.29
	45	32^{+}	45	0.85	1.00								
	90	10^{-}	42	0.98	1.11								
	135	57^{-}	58	0.54	0.62								
	180												
	225									57^{+}	58	0.54	0.62
	270									10^{+}	42	0.98	1.11
	315									32^{-}	45	0.85	1.00
Sep 23 & Mar 21	00												
	45	66^{+}	64	0.41	0.49								
	90	20^{+}	43	0.94	1.07	90^{+}	90	0.00	0.00				
	135	23^{-}	45	0.92	1.00	45^{+}	72	0.71	0.32				
	180	70^{-}	67	0.34	0.42	00	67	1.00	0.42	70^{+}	67	0.34	0.42
	225					45^{-}	72	0.71	0.32	23^{+}	45	0.92	1.00
	270					90^{-}	90	0.00	0.00	20^{-}	43	0.94	1.07
	315									66^{-}	64	0.41	0.49
Dec 22	00												
	45												
	90	48^{+}	37	0.67	1.33	90^{+}	90	0.00	0.00				
	135	03^{+}	30	0.99	1.73	45^{+}	50	0.71	0.84	88^{+}	85	0.03	0.09
	180	44^{-}	36	0.72	1.38	00	44	1.00	1.04	44^{+}	36	0.72	1.38
	225	88^{-}	85	0.03	0.09	45^{-}	50	0.71	0.84	03^{-}	30	0.99	1.73
	270					90^{-}	90	0.00	0.00	48^{-}	37	0.67	1.33
	315												

'+' Measured clockwise on the shadow angle protractor from orientation.

'-' Measured anti-clockwise on the shadow angle protractor from orientation.



<u>Fig. 23a</u>

Variations in the width of the penetrated beam of sunlight due to variations in the orientation of the facade with opening.

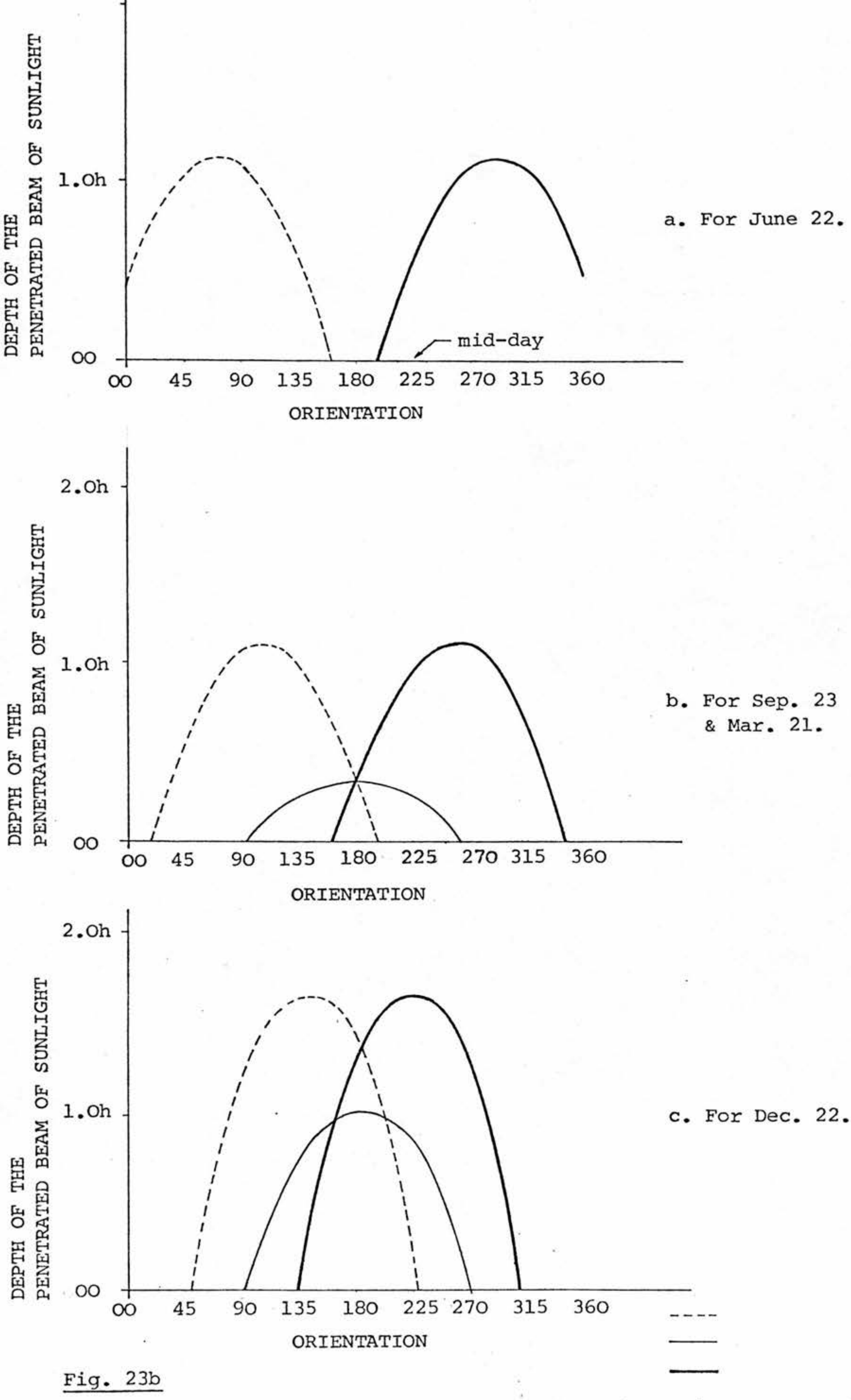


Fig. 23b

Variation in the depth (horizontally projected) of the penetrated beam of sunlight due to variation in the orientation of the facade with opening.

(iv) Effects on the degree of exposure of a facade (in terms of surface area) to solar irradiation due to variations in the spacing between parallel rows of buildings and due to variations in the depth of staggering between two adjacent and parallel vertical strips of the same facade and its angle of orientation.

This relationship is investigated as follows:

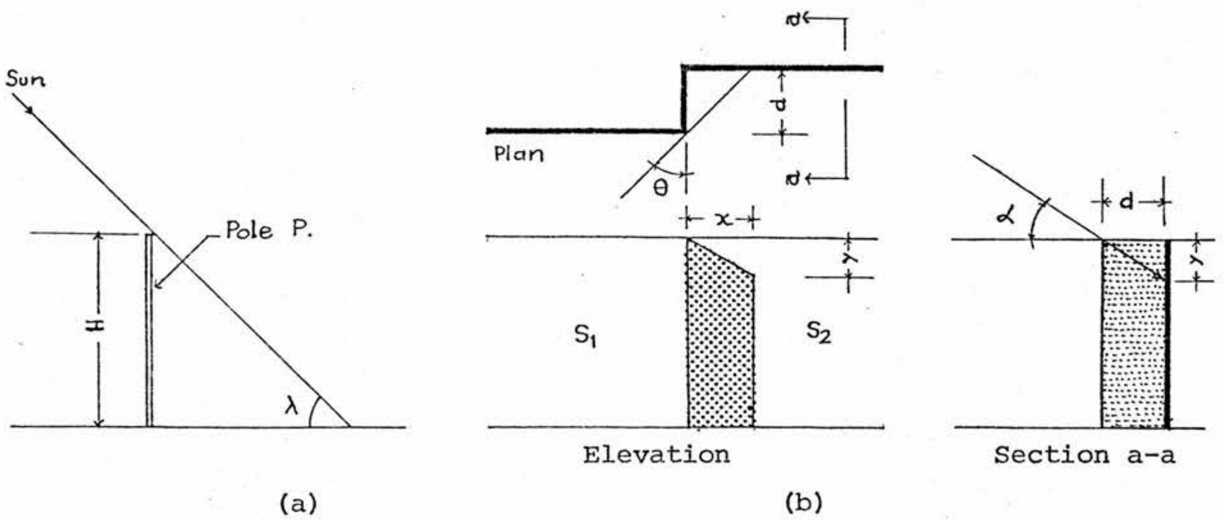


Fig. 24.

Let H be the height of the buildings and also the height of the vertical pole 'p' representing the height of the buildings.

λ be the altitude of the sun at a particular instant of the day.

S_1 and S_2 be the two vertical strips of the facade under consideration.

x be the width of the shadow cast by S_1 on S_2.

y be the distance of the end point of the sloping shadow line on S_2 from the top edge of S_2.

θ be the horizontal shadow angle.

α be the vertical shadow angle.

From the Figure 24a,

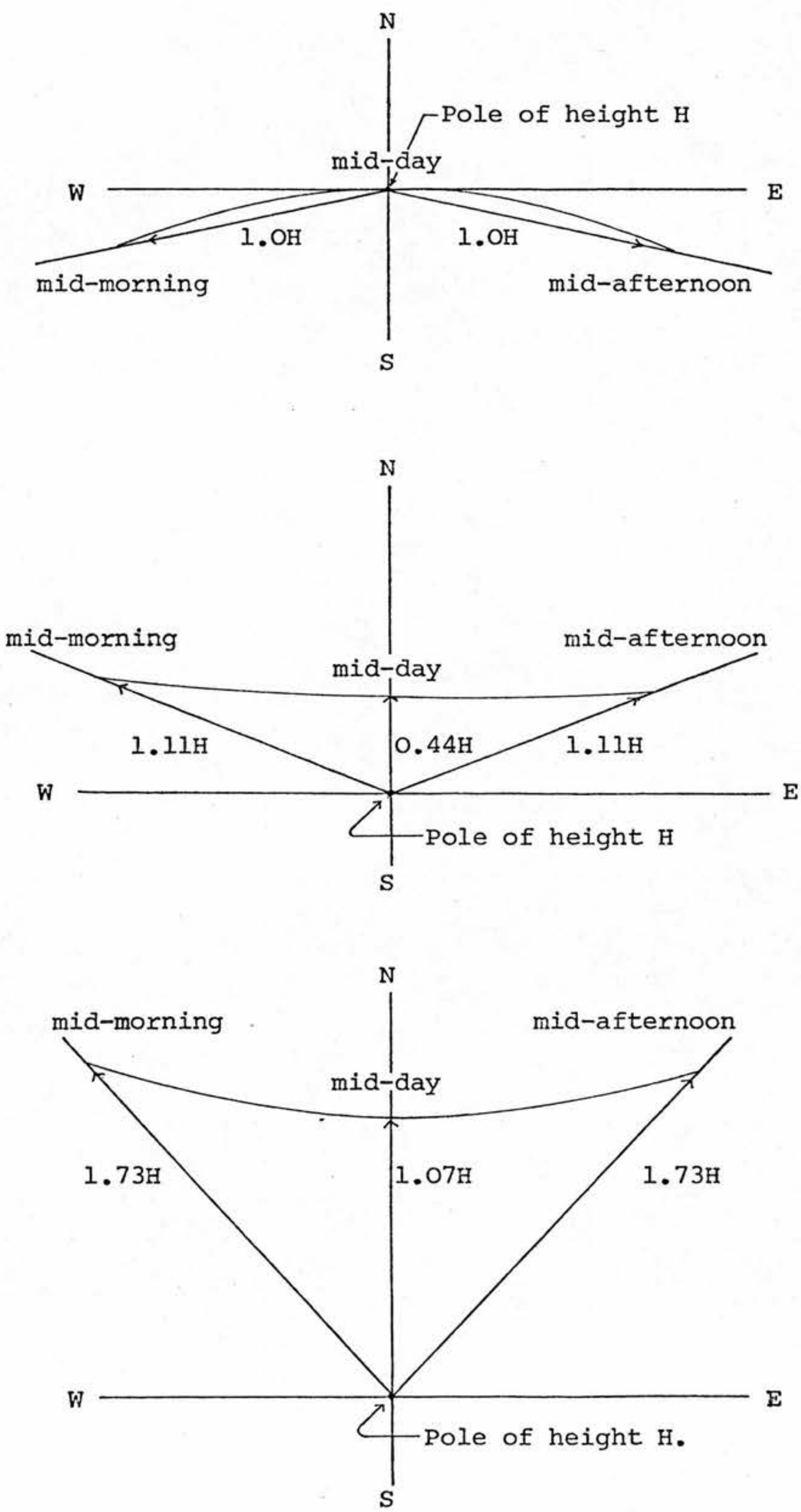
Length of the shadow = H cot λ

The direction of the shadow can be determined from the azimuth of the sun at the particular instant of the day. A table can be developed with the pertinent information (Table 6).

Table 6.

The Day	Instants of the day.	Sun's azimuth	Sun's altitude	Length of the shadow H Cot λ	Direction of the shadow
June 22	Mid-morning	79°	45°	1.0H	W 11° S
	Mid-day	180°	90°	0.0H	-
	Mid-afternoon	281°	45°	1.0H	E 11° S
Sept. 22 & Mar. 21	Mid-morning	112°	42°	1.11H	W 22° N
	Mid-day	180°	66°	0.44H	N
	Mid-afternoon	248°	42°	1.11H	E 22° N
Dec. 22	Mid-morning	138°	30°	1.73H	W 48° N
	Mid-day	180°	43°	1.07H	N
	Mid-afternoon	222°	30°	1.73H	E 48° N

The tabulated data can be expressed graphically as in the Figure 25. It is clear that if the shading of one row of buildings by the other is not desired, the spacing between the rows must be such as to keep the one out of the zone of influence (areas defined by the arcs) of the other.



a. For June 22

b. For Sept. 23 & Mar. 21.

c. For Dec. 22.

Fig. 25.

Depth and direction of shadows cast by a vertical pole of height H (representing the height of the buildings) at the various instants of the days.

Again from the Figure 24b, it can be seen that when $d = 0$, x will be equal to zero and there will be no shadow on the surface S_2. Also when d increases, values of x and y will increase reaching the maximum when y equals H. In this situation,

$$d = H \cot \alpha \qquad (1)$$

This may be called the critical value of d. When d increases further, the values of x and y remain unchanged. Therefore, for a certain orientation of the facade and for a certain instant of the day, changes in the values of x and y will occur for a value of d between $d = 0$ and $d = H \cot \alpha$. And it is in this range that the relationship between the area under shade on S_2 and the depth of staggering, d, needs to be studied. The pertinent relationships can be expressed as follows:-

$$x = d \tan \theta \qquad (2)$$

$$y = d \tan \alpha \qquad (3)$$

For the various instants such as the mid-morning, the mid-day and the mid-afternoon of a particular day, θ and α will have definite values for a specific orientation and the degree of exposure of a facade to solar irradiation expressed in terms of the values of x and y will depend only on the variations of d. Values of θ and α for various orientations at the different instants of the required days can be determined by using the sun-path diagram and the shadow angle protractor as have been discussed earlier. The required data can be tabulated as in the Table 7.

Table 7.

The Day	Orientation (deg)	Instant of the day: Mid-morning Tan Θ	Tan α	Cot α	Mid-day Tan Θ	Tan α	Cot α	Mid-afternoon Tan Θ	Tan α	Cot α
June 22	00	4.33	3.49	0.29				4.33	3.49	0.29
	45	0.62	1.00	1.00						
	90	0.18	0.90	1.11						
	135	1.54	1.60	0.62						
	180									
	225							1.54	1.60	0.62
	270							0.18	0.90	1.11
	315							0.62	1.00	1.00
Sep 23 & Mar 21	00									
	45	2.25	2.05	0.49						
	90	0.36	0.93	1.07	∝	∝	0.00			
	135	0.42	1.00	1.00	1.00	3.08	0.32			
	180	2.75	2.35	0.42	0.00	2.35	0.42	2.75	2.35	0.42
	225				1.00	3.08	0.32	0.42	1.00	1.00
	270				∝	∝	0.00	0.36	0.93	1.07
	315							2.25	2.05	0.49
Dec 22	00									
	45									
	90	1.11	0.75	1.33	∝	∝	0.00			
	135	0.05	0.58	1.73	1.00	1.19	0.84	28.64	11.43	0.09
	180	0.96	0.73	1.38	0.00	0.96	1.04	0.96	0.73	1.38
	225	28.64	11.43	0.09	1.00	1.19	0.84	0.05	0.58	1.73
	270				∝	∝	0.00	1.11	0.75	1.33
	315									

Using data from Table 7 in the equations $d = H \cot \alpha$, $x = d \tan \theta$ and $y = d \tan \alpha$, the values of critical d, x and y can be computed for the various orientations and at the required instants of the days. These values can be tabulated as in the Table 8. The degree of exposure of a facade to solar irradiation at the required instants of the days for the different orientations can be readily read from this table.

Table 8.

The day	Orientation (deg.)	Instants of the day								
		Mid-morning			Mid-day			Mid-afternoon		
		derit.	x	y	derit.	x	y	derit.	x	y
June 22	00	0.29H	4.33d	3.49d				0.29H	4.33d	3.49d
	45	1.00H	0.62d	1.00d						
	90	1.11H	0.18d	0.90d						
	135	0.62H	1.54d	1.60d						
	180									
	225							0.62H	1.54d	1.60d
	270							1.11H	0.18d	0.90d
	315							1.00H	0.62d	1.00d
Sep 23 & Mar 21	00									
	45	0.49H	2.25d	2.05d						
	90	1.07H	0.36d	0.93d	0.00	∝	∝			
	135	1.00H	0.42d	1.00d	0.32H	1.00d	3.08d			
	180	0.42H	2.75d	2.35d	0.42H	0.00	2.35d	0.42H	2.75d	2.35d
	225				0.32H	1.00d	3.08d	1.00H	0.42d	1.00d
	270				0.00	∝	∝	1.07H	0.36d	0.93d
	315							0.49H	2.25d	2.05d
Dec 22	00									
	45									
	90	1.33H	1.11d	0.75d	0.00	∝	∝			
	135	1.73H	0.05d	0.58d	0.84H	1.00d	1.19d	0.09H	28.64d	11.43d
	180	1.38H	0.96d	0.73d	1.04H	0.00	0.96d	1.38H	0.96d	0.73d
	225	0.09H	28.64d	11.43d	0.84H	1.00d	1.19d	1.73H	0.05d	0.58d
	270				0.00	∝	∝	1.33H	1.11d	0.75d
	315									

(v) Effects on the extent of solar-heat infiltration through the envelope expressed as a fraction of the incident solar radiation on the surface due to variations in the U-value, the ratio of the solar energy absorbed to the total energy incident on the surface (i.e. absorptivity of the surface) and the rate of heat flow through a unit area of the surface (i.e. the surface conductance).

As discussed in Section 4.1.1 this relationship can be expressed in terms of the solar heat gain factor given by:

$$\frac{q}{I} = \frac{a \times U}{f_o}$$

where, q = the extra heat flow rate per unit area (caused by the radiation) in W/m^2.

I = Intensity of radiation on the surface in W/m^2.

a = Absorptivity of the surface.

U = Air to air transmittance, in W/m^2 deg. C.

f_o = Outside surface conductance, in W/m^2 deg. C.

The outside surface conductance is a function of the nature of the surface and the amount of air movement past the surface. The A.S.H.V.E. guide gives values shown in the figure 26 (converted to S.l. units) for various types of common building surfaces at different wind speeds.

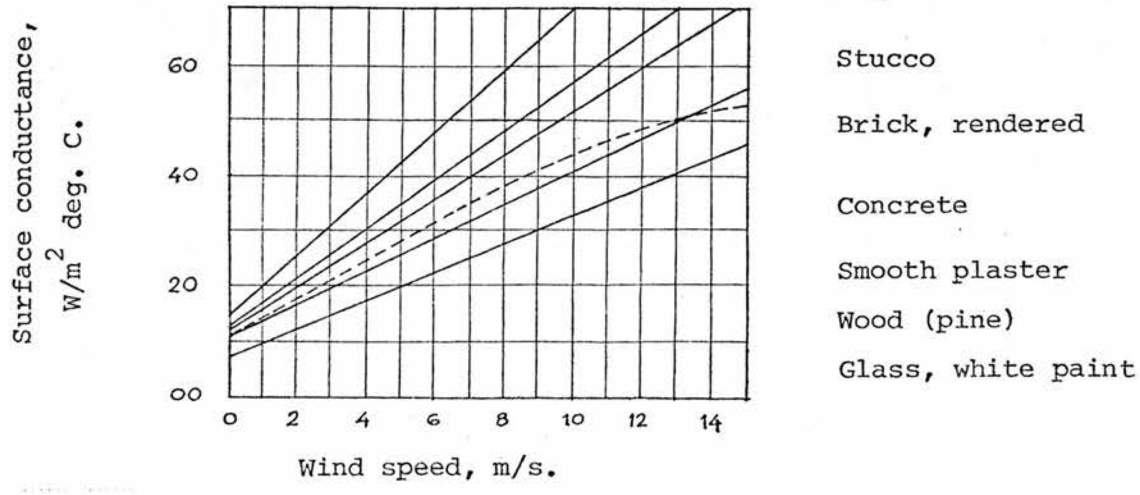


Fig. 26

In the given situation where air movement rates are typically low, it is reasonable to assume a constant value for f_o as $f_o = 20$ W/m^2 deg. C.

Then, $\frac{q}{I} = \frac{a \times U}{20} = 5$ Ua%

Thus the solar heat gain factor is a function of U and a.

U-value of a particular construction can be computed from its component factors as given by the equation:

$$U = \frac{1}{\frac{1}{f_o} + \frac{L_1}{k_1} + \frac{L_2}{k_2} + \frac{L_3}{k_3} + \frac{1}{C} + \frac{1}{f_i}}$$

where, f_o = outside surface conductance, W/m^2 deg. C.

f_i = inside surface conductance, W/m^2 deg. C.

L_1, L_2, L_3 = thickness of individual layers, metres.

k_1, k_2, k_3 = conductivities of the materials of the layers, W/m deg. C.

c = conductances of air spaces or cavities, W/m^2 deg. C.

Solar radiation absorptivity a (and also the longwave emissivity) for various surface materials and colours can be experimentally determined. For our purpose, however, values of different thermal factors for commonly used surfaces and constructions have been taken from various published sources (Billington, 1952; Lippsmeier, 1969; Givoni, 1969; Koenigsberger *et al.*, 1974 and Milbank and Lynn, 1974). These are given in Tables 1 and 2 in Appendix IV.

(vi) Effects on the decrement factor and time-lag produced by the envelope due to variations in the thickness of the envelope and its density.

The periodic heat flow rate through the envelope of a form can be expressed by the following equation (Koenigsberger *et al.*, 1974, p.87):

$$Q = A \times U \times \{(T_m - T_i) + \mu(T_\phi - T_m)\}$$

where Q = momentary heat flow rate in W.

A = area in m^2.

U = transmittance, W/m^2 deg. C.

T_m = daily mean outdoor temperature, ^oC.

T_i = indoor temperature (constant), ^oC.

T_ϕ = outdoor temperature (sol-air) ϕ hours earlier, ^oC.

μ = decrement factor.

ϕ = time-lag in hours.

It is obvious that the theory of periodic heat flow is far too complicated and cumbersome for general practical application. Although modern computers offer opportunities of solving the equations of transient heat transfer without having to over simplify them, it must be emphasized that the solutions obtained depend very much on the accuracy of the information fed into the computer. As van Stratten (1967,p.99) has pointed out, there is thus very little point in concentrating too much on the development of refined theoretical approaches to the problem whilst the accuracy with which the physical properties of building materials and elements, boundary conditions and design weather data can be defined still leaves much to be desired.

Effects on the decrement factor (μ) and time-lag (ϕ) due to variations in the thickness and density of the envelope can be calculated but the method will be rather involved. Also these can be established experimentally. In practice, however, simplified graphical relationships

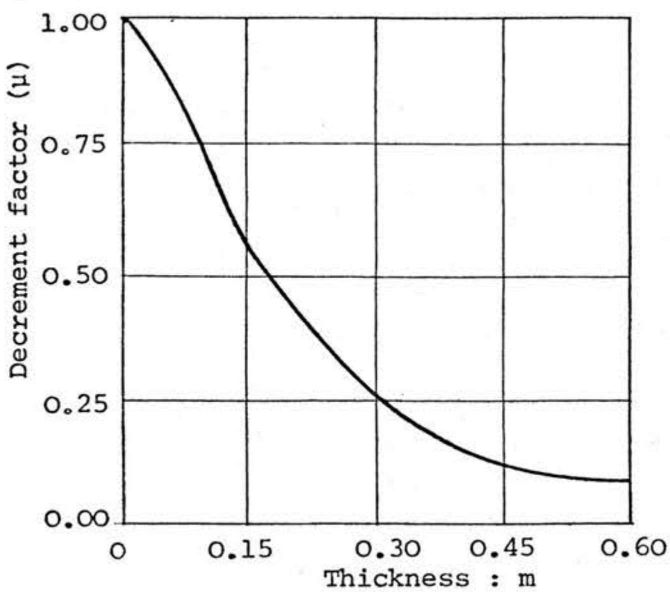


Fig. 27

Decrement factor for massive walls.

(Source: Koenigsberger *et al.*, 1974, 86).

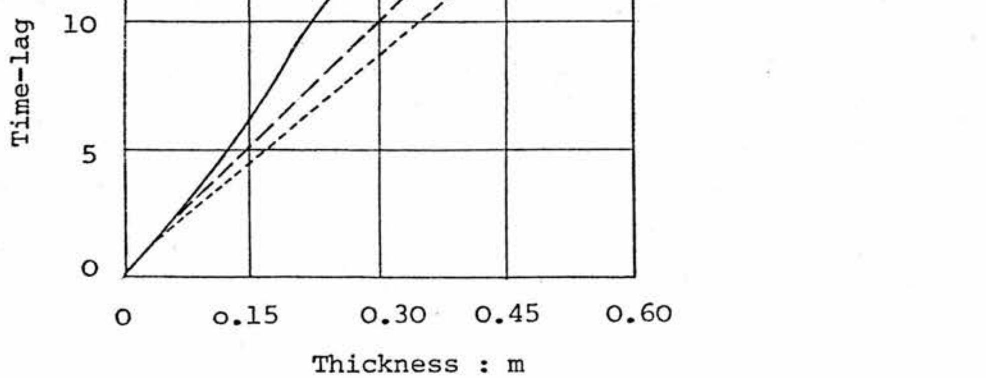


Fig. 28

Time-lag for massive walls.

(Source: Koenigsberger *et al.*, 1974, 86).

as given in the Figures 27 and 28 are found convenient and satisfactory even though not rigidly accurate. Also the Table 2 in Appendix IV lists the ϕ and μ values of several commonly used constructions.

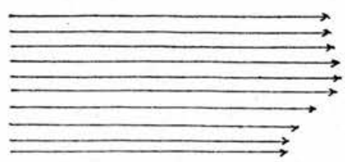
It may be noted here that the Figure 28 may appear misleading on the first sight because it suggests that a given thickness of material has shorter time-lag for heavier materials! In fact this is not unusual because the rate of heat flow through the building fabric is a function of its diffusivity or temperature conductivity expressed by $\frac{k}{\rho c}$. Higher density materials normally have higher conductivities or K-values, thereby resulting in a faster rate of heat transmission or a shorter time-lag.

5.2 THE CLIMATIC ELEMENT UNDER CONSIDERATION: AIR MOVEMENT

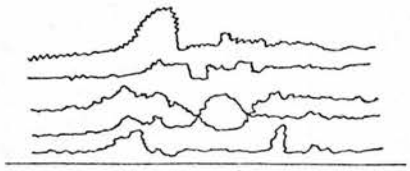
5.2.1 General Considerations:

The air movement experienced at a site will be a response to the large scale regional wind modified by local features. In certain regions, particularly in the humid tropics where the regional wind is quite weak, the local flow is a response to purely local conditions related to the topography, the upwind surface roughness, the thermal condition of the atmosphere and the characteristics of the built form.

Air flow can be either laminar or turbulent. In laminar flow the elements of air flow over each other like a pack of cards slipping, each with a different velocity from its neighbours. In turbulent flow, on the other hand, the movement of individual elements is completely random. Air movement through full scale built form will always be turbulent.



laminar flow



turbulent flow

Since air movement is caused by atmospheric pressure differences, pressure distribution is sometimes used as a means of pre-determining the air flow characteristics through indoor spaces. However, in a turbulent flow situation as is prevalent in nature, the properties of the flow (velocity, pressure and so on) are constantly changing. Moreover, when the flow through a built form is concerned, the porosity of the buildings further complicates the situation. Consequently, it is extremely difficult to use pressure distribution as a means for determining indoor flow characteristics.

Air flow characteristics in built forms are commonly investigated by using model forms in a wind tunnel. The validity of wind tunnel investigations for ventilation study purpose has been established by E.G. Smith (1951), J.J. Wannenburgh and J.F. van Stratten (1957) and others. The main factors to be considered in this kind of investigation are:-

Reynold's number

Wind velocity gradient

Tunnel blockage effects

Reynold's number represents the ratio of inertia and viscous forces in the air and can be expressed as $\frac{vd\rho}{\mu}$ where v is velocity, d is height of building, ρ is the density of the air and μ is its viscosity.

The main use of Reynold's number is to differentiate between laminar and turbulent flow. For full scale buildings, the flow is always turbulent because of their size, whereas with small models in a wind tunnel the flow can often be laminar. When this occurs, there is likely to be poor correspondence between models and fullscale results. However, it has been established that for negligible change in the density, viscosity and temperature in the air stream and for straight edged buildings, the air flow pattern is virtually independent of the Reynold's number and that even wide variations in air velocity do not affect flow and pressure distribution over the surfaces, provided that the models are not very small.

The speed of wind varies with height above the earth's surface. The variations depend primarily on the roughness of the surface and there are infinite numbers of possibilities. The wind velocity profile can be expressed as:

$$\bar{U}_Z = U_g \left(\frac{Z}{Z_g}\right)^{\alpha}$$

where, $\bar{U}_Z$ = Mean velocity at height Z.

U_g = Gradient wind velocity.

Z_g = Gradient height, i.e. the height at which wind is no longer affected by friction forces due to earth's surface.

α = coefficient depending on ground roughness.

Davenport (1961) proposed a series of values for Z_g and α for different surface roughness. His conclusions were derived from observations in high wind speeds. At moderate and low speeds, the velocity profile may still be approximated by a power law but the exponent depends on the thermal conditions of the atmosphere as well as on the upwind surface roughness (Jones, de Larringana, Wilson, 1971).

If the wind tunnel is of 'closed return type', i.e. if the tunnel is a continuous duct and if the model occupies more than about 5% of the cross-section of the tunnel, air flow accelerates past it in a manner unlike in nature. To keep errors due to this cause within reasonable limits, either the models have to be restricted in size or large enough tunnels have to be used.

A set of particular form-flow relationships established through a set of model tests in a wind tunnel is unlikely to be directly applicable to other form-flow situations because wind flow is a particularly difficult phenomenon to generalise about. Ideally, each design scheme needs to be modelled along with its significant site characteristics covering approximately five building blocks and investigated in a wind tunnel for form-flow relationships. In a complex physical form, this is rather unavoidable. For simple forms, however, a set of simple form-flow relationships carefully chosen and established in a wind tunnel can constitute a useful and adequate enough general guide line for exploring design possibilities in a generative manner.

Extensive wind tunnel investigations have been carried out on simple form-flow relationships in the Texas Engineering Experiment Station, Texas; National Building Research Institute, South Africa; Building Research Establishment, Garston; Building Research Station, Heifa and various other establishments all over the world. A serious limitation of many of these investigations is that they were carried out in laminar flow which is almost non-existent in real world situations. Also, very often, investigations were carried out with solid model blocks and interest was focussed on flow around building blocks and in spaces inbetween as well as on wind loading. The primary objective in most cases was to understand flow characteristics at outdoor pedestrian level in a given situation so as to be able to adopt measures for providing necessary shelter against gusts of cold wind at pedestrian level. In the humid tropics, however, conditions are quite different. Wind speeds are typically low and flow through buildings are much more important than flow through inbetween spaces. Very little work has been done so far in this area. As a part of the current work, wind tunnel investigations of groups of 'porous' building blocks were carried out in a turbulent flow. Details of these investigations and the results are reported hereafter.

5.2.2 Enumeration of the desired relationships:

(i) Effects on the average velocity of the incoming air at the inlet due to variations in the length, depth and height of the building blocks (all identical), their grouping pattern and spacing between the blocks.

(ii) Effects on the degree of coverage of the occupied space by the incoming air stream due to variations in the geometric details of the protective features such as canopies, sashes and louvres.

5.2.3 Investigating the relationships:

(i) Effects on the average velocity of the incoming air at the inlet due to variations in the length, depth and height of the blocks, their grouping pattern and spacing between the blocks.

These were investigated in a wind tunnel using scale models. The details of the experimental set-up, measurements, observations and results are discussed as below:

The Experimental Set-up and Measurements.

The aim of the investigation was to establish relationships between variations in the spacing of building blocks in a group and the corresponding mean velocities achieved at the inlet facades of the blocks. The mean velocity at an inlet facade is the average of the velocities at different inlet levels corresponding to the different storeys and this is expressed as a ratio of the mean velocity at the location of the facade (i.e. the average of the velocities corresponding to different inlet levels) with no building present.

The tunnel used was of a low-speed open-jet type. The tunnel opening was 1.52m x 1.06m and the working table was 1.52m x 1.72m. Speeds used were about 2-5 m/sec.

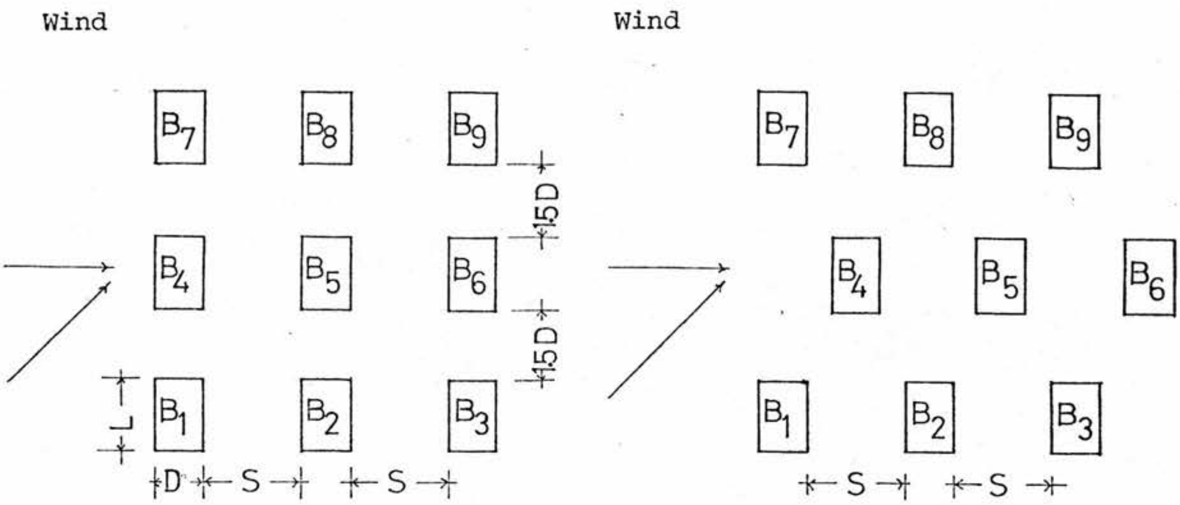
The form consisted of rectangular building units each of which at 1/100 scale had dimensions as given below:

Length : 13.5 cm

Depth : 9.0 cm

Height : 6.0 cm, 9.0 cm, and 15.0 cm, representing 2, 3 and 5-storey units respectively.

The windward and leeward facades of each unit had horizontal openings stretching across the entire facade and covering the middle-third of each storey height. Only two of the more obvious groupings out of an infinite number of possibilities were investigated. These were the grid-iron grouping and the checker-board grouping with two wind directions, namely, the normal and the oblique (45°) as follows:



Grid-iron Checker-board

Fig. 29.

Apart from the variations in spacing (S) and wind direction, other variations involving the geometric parameters of the building blocks themselves were:

(i) Length, L, with L equal to 13.5 cm and 27.0 cm corresponding to blocks with single and double unit lengths respectively.

(ii) Height H, with H equal to 6.0 cm, 9.0 cm and 15.0 cm corresponding to blocks with 2, 3 and 5 storeys respectively.

For velocity measurements a hot wire anemometer was used with the hot wire probe held perpendicular to the general direction of the flow. For taking measurements just inside an inlet opening, the probe was carefully placed past the opening and measurements recorded (at one point, central, for the single block length and at two points similarly for the double length) over an interval of time. The average of all readings taken at different inlet levels of a facade was expressed as a ratio of the average of corresponding readings at the position of the facade with no building present.

The results were recorded separately for each building block corresponding to a specific grouping under a specific wind direction. The values were then plotted on a graph with spacing (S) as abscissa and velocity ratio (r) as ordinate. With three storey heights and two block lengths, six combinations of the geometric parameters of the blocks themselves were involved. For each building block, the mean curve for these six combinations established the desired relationship between variations in spacing in a given grouping under a given wind direction and the corresponding windspeed at the inlet facade of that block valid within the tested range of variations of the geometric parameters of the blocks.

Thus, for the set of blocks comprising a group with a given wind direction, a set of curves, one for each block was obtained expressing the desired relationships. These curves can indicate optimum spacing of blocks in the given grouping under the given wind direction in relation to maximising the air speeds at the inlets. Also these will indicate the best and the worst affected buildings under the given situation and the range between the effects. Moreover, the different sets of curves can be compared forming a basis for designers to choose a grouping and spacing in a given situation (corresponding to the tested variations) with a view to maximising air speeds at the inlets of different building blocks in a layout.

<u>Observations and Results.</u>

It was decided to carry out the investigations in an airstream corresponding to the following full-scale law:

$$\bar{U}_Z = U_g \left(\frac{Z}{400}\right)^{0.28}$$

This has been found to give a fair representation of the gradient over a town of average size or over moderately rough country (Wise, Sexton, Lilleywhite, 1965).

To generate the desired velocity profile, a suitable grid comprising of horizontal bars was used at the tunnel opening. To check the resulting velocity profile velocity measurements were taken at nine positions as indicated in the figure below (Fig. 30).

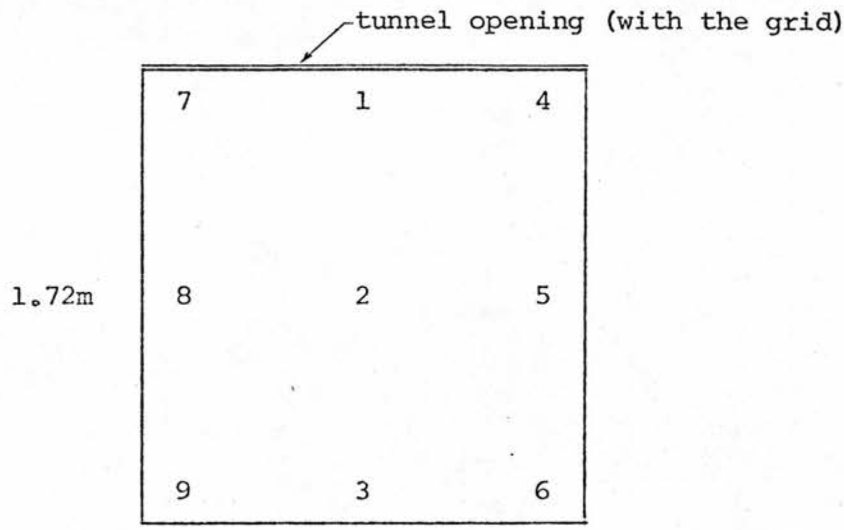


Fig. 30. Plan of the working table.

It was found that the velocity profiles obtained at these different positions with no building present were differing slightly with each other. However, they agreed reasonably well with the required values as can be seen in the figure over (Fig. 31) representing a typical profile. The figure shows the velocities obtained at the centre of the working table with no model present for the first 20 cm above the surface of the working table which, at 1/100 scale, corresponds to 20 m above the ground level.

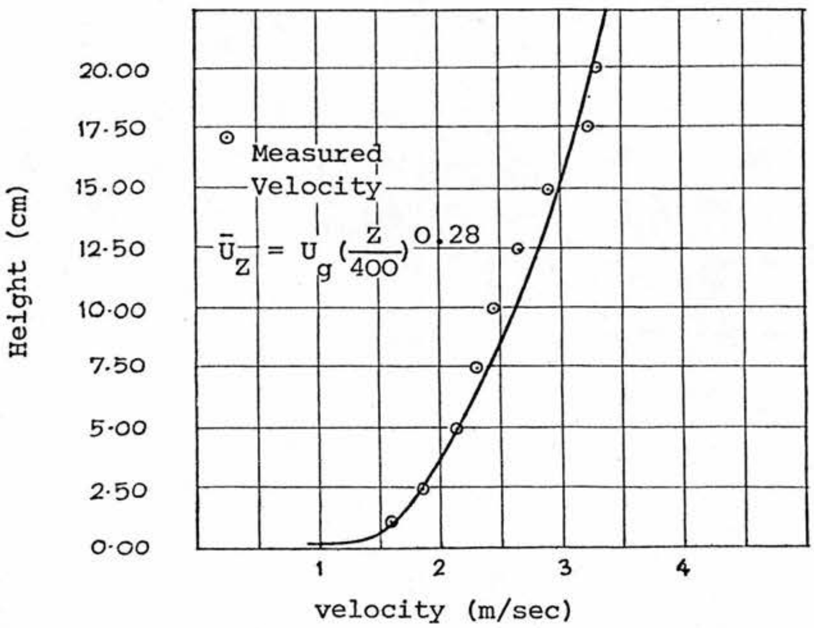


Fig. 31.

Having achieved the desired flow, the models were placed in it in the two different groupings and orientations as stated before and measurements were carried out as explained earlier. The measured values for the different groupings and orientations are tabulated as in the Tables 9 to 44. The tabulated values were then expressed in graphic forms as shown in the Figures 32 to 35. The relationships expressed in these figures can be summarized now and expressed as in the Figure 36.

Table 9. Measurements for block B_1 in grid-iron grouping with perpendicular wind direction.

Number of Storeys	Geometric Proportions	Corresponding symbols on graph	'Velocity ratio' at inlet for spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66	△	0.60	0.71	0.75	0.75
	L/D = 3.00 H/D = 0.66	△	0.64	0.70	0.88	0.94
3	L/D = 1.50 H/D = 1.00	□	0.94	1.10	1.16	1.20
	L/D = 3.00 H/D = 1.00	□	0.84	0.90	0.98	1.03
5	L/D = 1.50 H/D = 1.66	○	0.65	0.72	0.77	0.83
	L/D = 3.00 H/D = 1.66	○	0.66	0.96	0.96	1.00

Table 10. Measurements for block B_2 in grid-iron grouping with perpendicular wind direction.

2	L/D = 1.50 H/D = 0.66	△	0.45	0.53	0.59	0.63
	L/D = 3.00 H/D = 0.66	△	0.43	0.51	0.55	0.67
3	L/D = 1.50 H/D = 1.00	□	0.67	0.89	0.92	0.92
	L/D = 3.00 H/D = 1.00	□	0.48	0.61	0.65	0.69
5	L/D = 1.50 H/D = 1.66	○	0.55	0.68	0.65	0.65
	L/D = 3.00 H/D = 1.66	○	0.43	0.56	0.52	0.60

Table 11. Measurements for block B_3 in grid-iron grouping with perpendicular wind direction

Number of Storeys	Geometric Proportions	Corresponding symbols on graph	'Velocity ratio' at inlet for spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66	△	0.43	0.54	0.62	0.62
	L/D = 3.00 H/D = 0.66	△	0.41	0.50	0.55	0.70
3	L/D = 1.50 H/D = 1.00	□	0.64	0.80	0.81	0.87
	L/D = 3.00 H/D = 1.00	□	0.48	0.55	0.59	0.64
5	L/D = 1.50 H/D = 1.66	○	0.53	0.58	0.60	0.67
	L/D = 3.00 H/D = 1.66	○	0.43	0.53	0.50	0.57

Table 12. Measurements for block B_4 in grid-iron grouping with perpendicular wind direction.

2	L/D = 1.50 H/D = 0.66	△	0.71	0.80	0.75	0.86
	L/D = 3.00 H/D = 0.66	△	0.74	1.00	0.97	0.97
3	L/D = 1.50 H/D = 1.00	□	1.00	1.14	1.14	1.20
	L/D = 3.00 H/D = 1.00	□	0.88	1.03	1.11	1.19
5	L/D = 1.50 H/D = 1.66	○	0.77	1.00	1.07	1.07
	L/D = 3.00 H/D = 1.66	○	0.73	1.03	1.02	1.03

Table 13. Measurements for block B_5 in grid-iron grouping with perpendicular wind direction.

Number of Storeys	Geometric Proportions	Corresponding symbols on graph	'Velocity ratio' at inlet for spacing 'S' equal to:			
			H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66	△	0.47	0.51	0.58	0.62
	L/D = 3.00 H/D = 0.66	△̸	0.51	0.59	0.70	0.67
3	L/D = 1.50 H/D = 1.00	□	0.70	0.80	0.90	1.01
	L/D = 3.00 H/D = 1.00	□̸	0.60	0.64	0.77	0.81
5	L/D = 1.50 H/D = 1.66	○	0.52	0.67	0.75	0.80
	L/D = 3.00 H/D = 1.66	○̸	0.56	0.62	0.68	0.77

Table 14. Measurements for block B_6 in grid-iron grouping with perpendicular wind direction.

2	L/D = 1.50 H/D = 0.66	△	0.37	0.41	0.54	0.58
	L/D = 3.00 H/D = 0.66	△̸	0.42	0.50	0.57	0.54
3	L/D = 1.50 H/D = 1.00	□	0.60	0.70	0.88	0.98
	L/D = 3.00 H/D = 1.00	□̸	0.38	0.45	0.46	0.55
5	L/D = 1.50 H/D = 1.66	○	0.38	0.55	0.67	0.65
	L/D = 3.00 H/D = 1.66	○̸	0.45	0.45	0.55	0.57

Table 15. Measurements for block B_7 in grid-iron grouping with perpendicular wind direction.

Number of Storeys	Geometric Proportions	Corresponding symbols on graph.	'Velocity ratio' at inlet for spacing 'S' equal to:			
			H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66	△	0.77	0.81	0.84	0.84
	L/D = 3.00 H/D = 0.66	△	0.82	0.91	0.93	0.98
3	L/D = 1.50 H/D = 1.00	□	0.98	1.03	1.04	1.07
	L/D = 3.00 H/D = 1.00	□	0.90	1.03	1.02	1.09
5	L/D = 1.50 H/D = 1.66	○	0.83	1.03	1.07	1.03
	L/D = 3.00 H/D = 1.66	○	0.85	1.02	1.10	1.11

Table 16. Measurements for block B_8 in grid-iron grouping with perpendicular wind direction.

2	L/D = 1.50 H/D = 0.66	△	0.54	0.60	0.70	0.79
	L/D = 3.00 H/D = 0.66	△	0.50	0.54	0.67	0.75
3	L/D = 1.50 H/D = 1.00	□	0.78	1.00	1.07	1.04
	L/D = 3.00 H/D = 1.00	□	0.51	0.64	0.75	0.85
5	L/D = 1.50 H/D = 1.66	○	0.63	0.81	0.90	0.83
	L/D = 3.00 H/D = 1.66	○	0.56	0.58	0.70	0.79

Table 17. Measurements for block B_9 in grid-iron grouping with perpendicular wind direction.

Number of Storeys	Geometric Proportions	Corresponding symbols on graph.	'Velocity ratio' at inlet spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66	△	0.50	0.60	0.70	0.77
	L/D = 3.00 H/D = 0.66	△	0.47	0.54	0.59	0.64
3	L/D = 1.50 H/D = 1.00	□	0.87	1.00	1.03	1.03
	L/D = 3.00 H/D = 1.00	□	0.54	0.67	0.77	0.83
5	L/D = 1.50 H/D = 1.66	○	0.65	0.79	0.75	0.77
	L/D = 3.00 H/D = 1.66	○	0.56	0.66	0.75	0.79

Table 18. Measurements for block B_1 in checker-board grouping with perpendicular wind direction.

2	L/D = 1.50 H/D = 0.66	△	0.64	0.76	0.69	0.70
	L/D = 3.00 H/D = 0.66	△	0.52	0.62	0.54	0.49
3	L/D = 1.50 H/D = 1.00	□	0.87	1.00	0.74	0.80
	L/D = 3.00 H/D = 1.00	□	0.70	0.88	0.80	0.66
5	L/D = 1.50 H/D = 1.66	○	0.69	0.83	0.69	0.72
	L/D = 3.00 H/D = 1.66	○	0.90	1.04	0.91	0.90

<u>Table 19.</u> Measurements for block B_2 in checker-board grouping with perpendicular wind direction.

Number of Storeys	Geometric Proportions	Corresponding symbols on graphs	'Velocity ratio' at inlet for spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66	△	0.40	0.51	0.57	0.53
	L/D = 3.00 H/D = 0.66	△/	0.36	0.56	0.51	0.51
3	L/D = 1.50 H/D = 1.00	□	0.63	0.88	0.62	0.63
	L/D = 3.00 H/D = 1.00	□/	0.46	0.62	0.53	0.58
5	L/D = 1.50 H/D = 1.66	○	0.42	0.58	0.57	0.63
	L/D = 3.00 H/D = 1.66	○/	0.44	0.92	0.78	0.80

<u>Table 20.</u> Measurements for block B_3 in checker-board grouping with perpendicular wind direction.

2	L/D = 1.50 H/D = 0.66	△	0.59	0.71	0.66	0.53
	L/D = 3.00 H/D = 0.66	△/	0.37	0.65	0.58	0.50
3	L/D = 1.50 H/D = 1.00	□	0.67	0.90	0.71	0.69
	L/D = 3.00 H/D = 1.00	□/	0.40	0.46	0.42	0.48
5	L/D = 1.50 H/D = 1.66	○	0.50	0.62	0.52	0.47
	L/D = 3.00 H/D = 1.66	○/	0.31	0.49	0.49	0.42

Table 21. Measurements for block B_4 in checker-board grouping with perpendicular wind direction.

Number of Storeys	Geometric Proportions	Corresponding symbols on graph.	'Velocity ratio' at inlet for spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66	△	0.73	0.82	0.79	0.70
	L/D = 3.00 H/D = 0.66	△	0.69	0.95	0.68	0.55
3	L/D = 1.50 H/D = 1.00	□	0.90	1.01	1.06	0.88
	L/D = 3.00 H/D = 1.00	□	0.89	0.92	0.94	0.84
5	L/D = 1.50 H/D = 1.66	○	0.77	0.87	0.73	0.62
	L/D = 3.00 H/D = 1.66	○	0.99	1.02	0.99	0.89

Table 22. Measurements for block B_5 in checker-board grouping with perpendicular wind direction.

2	L/D = 1.50 H/D = 0.66	△	0.53	0.57	0.59	0.52
	L/D = 3.00 H/D = 0.66	△	0.41	0.51	0.54	0.50
3	L/D = 1.50 H/D = 1.00	□	0.77	1.00	0.88	0.80
	L/D = 3.00 H/D = 1.00	□	0.58	0.68	0.64	0.60
5	L/D = 1.50 H/D = 1.66	○	0.73	0.68	0.67	0.57
	L/D = 3.00 H/D = 1.66	○	0.76	0.80	0.72	0.67

Table 23. Measurements for block B_6 in checker-board grouping with perpendicular wind direction.

Number of Storeys	Geometric Proportions	Corresponding symbols on graph.	'Velocity ratio' at inlet for spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66	△	0.61	0.70	0.63	0.65
	L/D = 3.00 H/D = 0.66	△	0.55	0.57	0.54	0.51
3	L/D = 1.50 H/D = 1.00	□	0.66	0.95	0.93	0.75
	L/D = 3.00 H/D = 1.00	□	0.55	0.70	0.68	0.60
5	L/D = 1.50 H/D = 1.66	○	0.57	0.67	0.62	0.57
	L/D = 3.00 H/D = 1.66	○	0.55	0.76	0.55	0.50

Table 24. Measurements for block B_7 in checker-board grouping with perpendicular wind direction.

2	L/D = 1.50 H/D = 0.66	△	0.71	0.82	0.85	0.63
	L/D = 3.00 H/D = 0.66	△	0.66	0.83	0.79	0.60
3	L/D = 1.50 H/D = 1.00	□	0.90	1.09	0.99	0.80
	L/D = 3.00 H/D = 1.00	□	0.88	1.00	0.86	0.76
5	L/D = 1.50 H/D = 1.66	○	0.80	0.87	0.83	0.70
	L/D = 3.00 H/D = 1.66	○	0.90	0.98	0.99	0.82

Table 25. Measurements for block B_8 in checker-board grouping with perpendicular wind direction.

Number of Storeys	Geometric Proportions	Corresponding symbols on graph.	'Velocity ratio' at inlet for spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66	△	0.60	0.86	0.79	0.71
	L/D = 3.00 H/D = 0.66	△	0.40	0.71	0.68	0.68
3	L/D = 1.50 H/D = 1.00	□	0.95	1.15	1.00	0.84
	L/D = 3.00 H/D = 1.00	□	0.70	0.80	0.84	0.70
5	L/D = 1.50 H/D = 1.66	○	0.70	0.82	0.83	0.73
	L/D = 3.00 H/D = 1.66	○	0.72	0.95	0.76	0.73

Table 26. Measurements for block B_9 in checker-board grouping with perpendicular wind direction.

2	L/D = 1.50 H/D = 0.66	△	0.72	0.85	0.77	0.63
	L/D = 3.00 H/D = 0.66	△	0.50	0.69	0.62	0.59
3	L/D = 1.50 H/D = 1.00	□	0.95	1.20	1.00	0.88
	L/D = 3.00 H/D = 1.00	□	0.58	0.74	0.68	0.60
5	L/D = 1.50 H/D = 1.66	○	0.73	0.87	0.82	0.70
	L/D = 3.00 H/D = 1.66	○	0.57	0.98	0.69	0.59

Table 27. Measurements for block B_1 in grid-iron grouping with oblique wind direction.

Number of Storeys	Geometric Proportions	Corresponding symbols on graph.	'Velocity ratio' at inlet for spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66		0.80	0.88	0.90	0.90
	L/D = 3.00 H/D = 0.66		0.84	1.06	1.15	0.98
3	L/D = 1.50 H/D = 1.00		0.88	0.97	0.93	0.97
	L/D = 3.00 H/D = 1.00		0.94	1.05	1.13	1.00
5	L/D = 1.50 H/D = 1.66		0.94	1.02	1.08	0.96
	L/D = 3.00 H/D = 1.66		1.05	1.04	1.08	1.06

Table 28. Measurements for block B_2 in grid-iron grouping with oblique wind direction.

2	L/D = 1.50 H/D = 0.66		0.90	1.02	1.05	1.03
	L/D = 3.00 H/D = 0.66		0.97	1.14	1.16	1.03
3	L/D = 1.50 H/D = 1.00		0.98	1.09	0.93	0.98
	L/D = 3.00 H/D = 1.00		0.93	1.21	1.17	0.98
5	L/D = 1.50 H/D = 1.66		1.05	1.18	1.06	1.00
	L/D = 3.00 H/D = 1.66		1.13	1.11	1.01	1.10

Table 29. Measurements for block B_3 in grid-iron grouping with oblique wind direction.

Number of storeys	Geometric Proportions	Corresponding symbols on graphs	'Velocity ratio' at inlet for spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66	▲	0.77	0.97	0.87	0.84
	L/D = 3.00 H/D = 0.66	▲/	0.94	1.07	1.02	1.12
3	L/D = 1.50 H/D = 1.00	■	0.86	0.92	0.97	0.85
	L/D = 3.00 H/D = 1.00	■/	0.96	0.94	1.00	0.98
5	L/D = 1.50 H/D = 1.66	●	0.94	0.97	0.92	0.90
	L/D = 3.00 H/D = 1.66	●/	1.01	1.16	1.11	1.07

Table 30. Measurements for block B_4 in grid-iron grouping with oblique wind direction.

2	L/D = 1.50 H/D = 0.66	▲	0.81	0.92	0.87	0.89
	L/D = 3.00 H/D = 0.66	▲/	0.89	1.05	1.02	1.08
3	L/D = 1.50 H/D = 1.00	■	1.10	1.18	1.17	0.98
	L/D = 3.00 H/D = 1.00	■/	0.95	1.01	1.11	1.00
5	L/D = 1.50 H/D = 1.66	●	0.87	0.97	1.13	1.03
	L/D = 3.00 H/D = 1.66	●/	0.76	0.96	1.06	0.98

<u>Table 31.</u> Measurements for block B_5 in grid-iron grouping with oblique wind direction.

Number of Storeys	Geometric Proportions	Corresponding symbols on graph.	'Velocity ratio' at inlet for spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66	▲	0.55	0.71	0.71	0.71
	L/D = 3.50 H/D = 0.66	▲	0.61	0.95	0.98	1.00
3	L/D = 1.50 H/D = 1.00	■	0.75	0.85	0.77	0.84
	L/D = 3.00 H/D = 1.00	■	0.59	0.74	0.80	0.87
5	L/D = 1.50 H/D = 1.66	●	0.65	0.69	0.83	0.83
	L/D = 3.00 H/D = 1.66	●	0.61	0.74	0.70	0.85

<u>Table 32.</u> Measurements for block B_6 in grid-iron grouping with oblique wind direction.

2	L/D = 1.50 H/D = 0.66	▲	0.45	0.64	0.77	0.74
	L/D = 3.00 H/D = 0.66	▲	0.51	0.89	0.79	0.85
3	L/D = 1.50 H/D = 1.00	■	0.68	0.73	0.99	1.04
	L/D = 3.00 H/D = 1.00	■	0.45	0.65	0.65	0.60
5	L/D = 1.50 H/D = 1.66	●	0.47	0.66	0.67	0.71
	L/D = 3.00 H/D = 1.66	●	0.59	0.69	0.68	0.67

Table 33. Measurements for block B_7 in grid-iron grouping with oblique wind direction.

Number of Storeys	Geometric Proportions	Corresponding symbols on graph	'Velocity ratio' at inlet for spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66	▲	0.86	0.91	0.97	0.95
	L/D = 3.00 H/D = 0.66	▲	1.00	1.08	1.10	1.18
3	L/D = 1.50 H/D = 1.00	■	1.04	1.08	1.14	1.07
	L/D = 3.00 H/D = 1.00	■	1.01	1.03	1.16	1.16
5	L/D = 1.50 H/D = 1.66	●	0.91	1.06	1.07	1.10
	L/D = 3.00 H/D = 1.66	●	0.90	1.02	1.13	1.00

Table 34. Measurements for block B_8 in grid-iron grouping with oblique wind direction.

2	L/D = 1.50 H/D = 0.66	▲	0.52	0.68	0.71	0.71
	L/D = 3.00 H/D = 0.66	▲	0.55	0.84	0.97	0.87
3	L/D = 1.50 H/D = 1.00	■	0.85	1.05	1.07	1.07
	L/D = 3.00 H/D = 1.00	■	0.65	0.80	0.90	0.83
5	L/D = 1.50 H/D = 1.66	●	0.71	0.92	0.90	0.93
	L/D = 3.00 H/D = 1.66	●	0.65	0.77	0.79	0.73

Table 35. Measurements for block B_9 in grid-iron grouping with oblique wind direction.

Number of Storeys	Geometric Proportions	Corresponding symbols on graph.	'Velocity ratio' at inlet for spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66	▲	0.52	0.65	0.64	0.64
	L/D = 3.00 H/D = 0.66	▲	0.45	0.64	0.69	0.64
3	L/D = 1.50 H/D = 1.00	■	0.60	0.73	0.89	0.78
	L/D = 3.00 H/D = 1.00	■	0.54	0.62	0.74	0.83
5	L/D = 1.50 H/D = 1.66	●	0.45	0.58	0.65	0.68
	L/D = 3.00 H/D = 1.66	●	0.52	0.52	0.57	0.60

Table 36. Measurements for block B_1 in checker-board grouping with oblique wind direction.

2	L/D = 1.50 H/D = 0.66	▲	0.79	0.85	0.77	0.65
	L/D = 3.00 H/D = 0.66	▲	0.59	0.77	0.56	0.50
3	L/D = 1.50 H/D = 1.00	■	0.57	0.60	0.47	0.41
	L/D = 3.00 H/D = 1.00	■	0.49	0.58	0.45	0.41
5	L/D = 1.50 H/D = 1.66	●	0.65	0.68	0.60	0.52
	L/D = 3.00 H/D = 1.66	●	0.54	0.55	0.51	0.43

Table 37. Measurements for block B_2 in checker-board grouping with oblique wind direction.

Number of Storeys	Geometric Proportions	Corresponding symbols on graph.	'Velocity ratio' at inlet for spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66		0.73	0.94	0.97	0.90
	L/D = 3.00 H/D = 0.66		0.67	0.78	0.82	0.70
3	L/D = 1.50 H/D = 1.00		0.71	0.80	0.81	0.73
	L/D = 3.00 H/D = 1.00		0.60	0.74	0.75	0.67
5	L/D = 1.50 H/D = 1.66		0.74	0.79	0.73	0.63
	L/D = 3.00 H/D = 1.66		0.70	0.72	0.75	0.69

Table 38. Measurements for block B_3 in checker-board grouping with oblique wind direction.

2	L/D = 1.50 H/D = 0.66		0.69	0.85	0.75	0.56
	L/D = 3.00 H/D = 0.66		0.61	0.70	0.63	0.50
3	L/D = 1.50 H/D = 1.00		0.57	0.67	0.62	0.48
	L/D = 3.00 H/D = 1.00		0.50	0.58	0.52	0.47
5	L/D = 1.50 H/D = 1.66		0.63	0.72	0.71	0.65
	L/D = 3.00 H/D = 1.66		0.53	0.68	0.65	0.51

<u>Table 39.</u> Measurements for block B_4 in checker-board grouping with oblique wind direction.

Number of Storeys	Geometric Proportions	Corresponding symbols on graph.	'Velocity ratio' at inlet for spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66	▲	0.75	0.79	0.72	0.67
	L/D = 3.00 H/D = 0.66	▲	0.66	0.68	0.70	0.62
3	L/D = 1.50 H/D = 1.00	■	0.56	0.63	0.67	0.51
	L/D = 3.00 H/D = 1.00	■	0.57	0.61	0.60	0.50
5	L/D = 1.50 H/D = 1.66	●	0.47	0.57	0.53	0.45
	L/D = 3.00 H/D = 1.66	●	0.52	0.52	0.50	0.41

<u>Table 40.</u> Measurements for block B_5 in checker-board grouping with oblique wind direction.

2	L/D = 1.50 H/D = 0.66	▲	0.45	0.63	0.62	0.60
	L/D = 3.00 H/D = 0.66	▲	0.56	0.68	0.60	0.51
3	L/D = 1.50 H/D = 1.00	■	0.39	0.57	0.44	0.44
	L/D = 3.00 H/D = 1.00	■	0.38	0.52	0.54	0.50
5	L/D = 1.50 H/D = 1.66	●	0.39	0.53	0.51	0.43
	L/D = 3.00 H/D = 1.66	●	0.34	0.46	0.41	0.40

Table 41. Measurements for block B_6 in checker-board grouping with oblique wind direction.

Number of Storeys	Geometric Proportions	Corresponding symbols on graph.	'Velocity ratio' at inlet for spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66		0.42	0.70	0.63	0.54
	L/D = 3.00 H/D = 0.66		0.48	0.70	0.56	0.51
3	L/D = 1.50 H/D = 1.00		0.32	0.53	0.40	0.40
	L/D = 3.00 H/D = 1.00		0.28	0.47	0.43	0.41
5	L/D = 1.50 H/D = 1.66		0.26	0.40	0.37	0.33
	L/D = 3.00 H/D = 1.66		0.30	0.36	0.33	0.30

Table 42. Measurements for block B_7 in checker-board grouping with oblique wind direction.

2	L/D = 1.50 H/D = 0.66		0.77	0.90	0.84	0.76
	L/D = 3.00 H/D = 0.66		1.07	1.02	0.98	0.86
3	L/D = 1.50 H/D = 1.00		0.67	0.71	0.68	0.59
	L/D = 3.00 H/D = 1.00		0.72	0.80	0.81	0.67
5	L/D = 1.50 H/D = 1.66		0.58	0.73	0.78	0.61
	L/D = 3.00 H/D = 1.66		0.75	0.83	0.80	0.71

Table 43. Measurements for block B_8 in checker-board grouping with oblique wind direction.

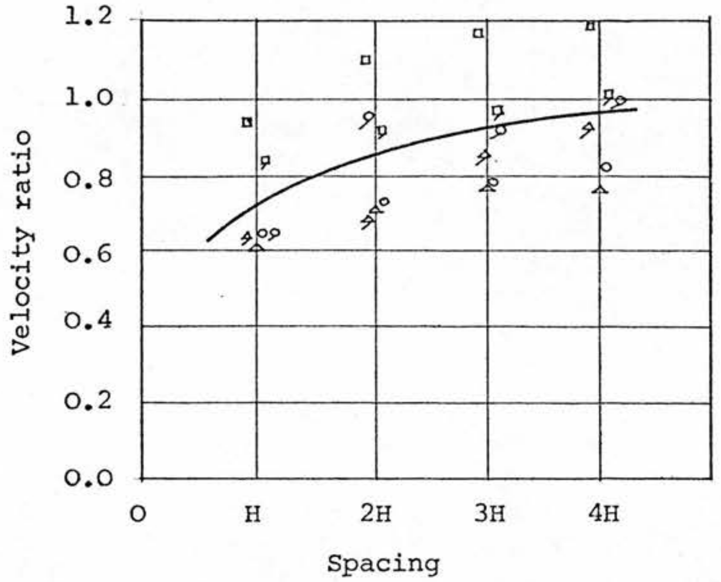
Number of Storeys	Geometric Proportions	Corresponding symbols on graph.	'Velocity ratio' at inlet for spacing 'S' equal to: H	2H	3H	4H
2	L/D = 1.50 H/D = 0.66		0.47	0.69	0.74	0.50
	L/D = 3.00 H/D = 0.66		0.52	0.66	0.56	0.52
3	L/D = 1.50 H/D = 1.00		0.46	0.64	0.55	0.50
	L/D = 3.00 H/D = 1.00		0.48	0.52	0.56	0.57
5	L/D = 1.50 H/D = 1.66		0.43	0.56	0.52	0.48
	L/D = 3.00 H/D = 1.66		0.52	0.59	0.59	0.53

Table 44. Measurements for block B_9 in checker-board grouping with oblique wind direction.

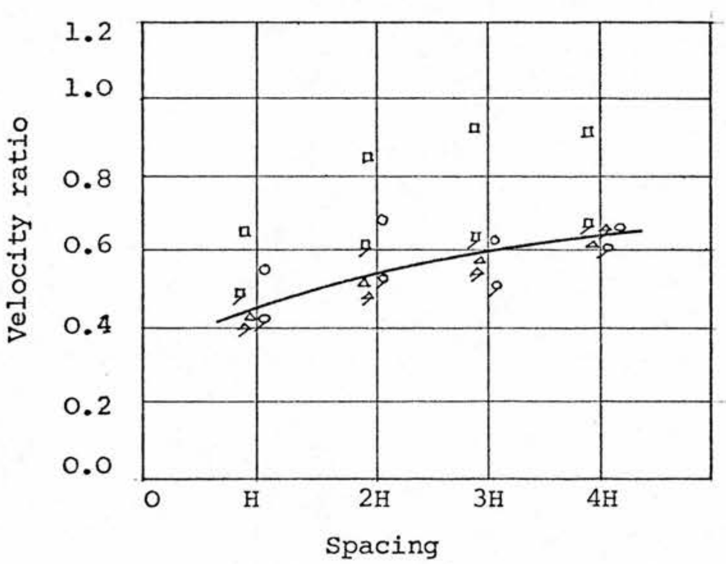
2	L/D = 1.50 H/D = 0.66		0.32	0.50	0.45	0.34
	L/D = 3.00 H/D = 0.66		0.30	0.47	0.43	0.33
3	L/D = 1.50 H/D = 1.00		0.25	0.43	0.37	0.30
	L/D = 3.00 H/D = 1.00		0.24	0.38	0.30	0.32
5	L/D = 1.50 H/D = 1.66		0.23	0.41	0.37	0.33
	L/D = 3.00 H/D = 1.66		0.24	0.36	0.36	0.29

Fig. 32

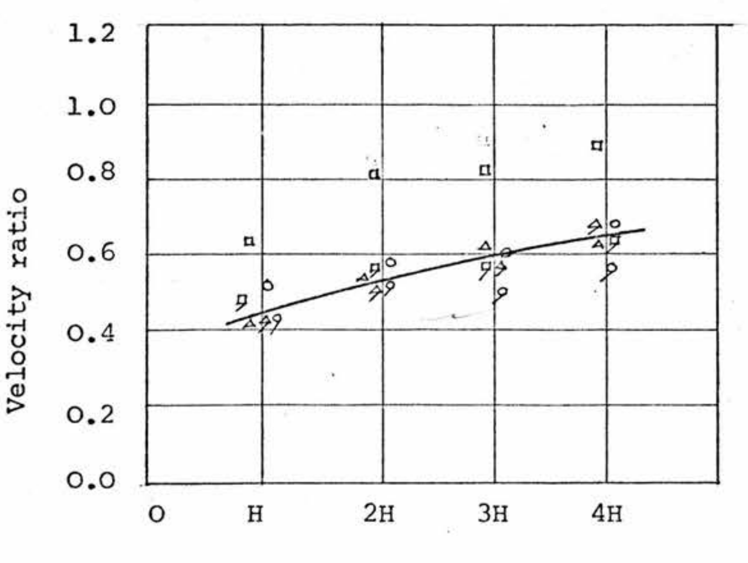
Measurements for blocks B_1 to B_9 in grid-iron grouping with perpendicular wind direction.



a. For block B_1

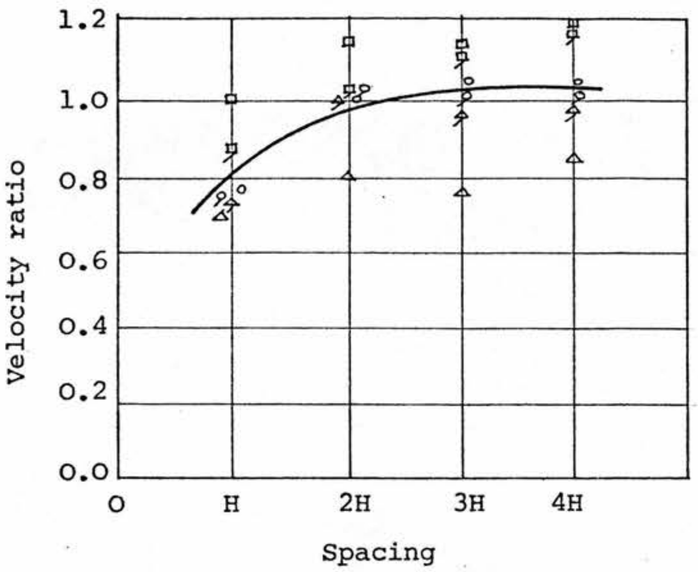


b. For block B_2

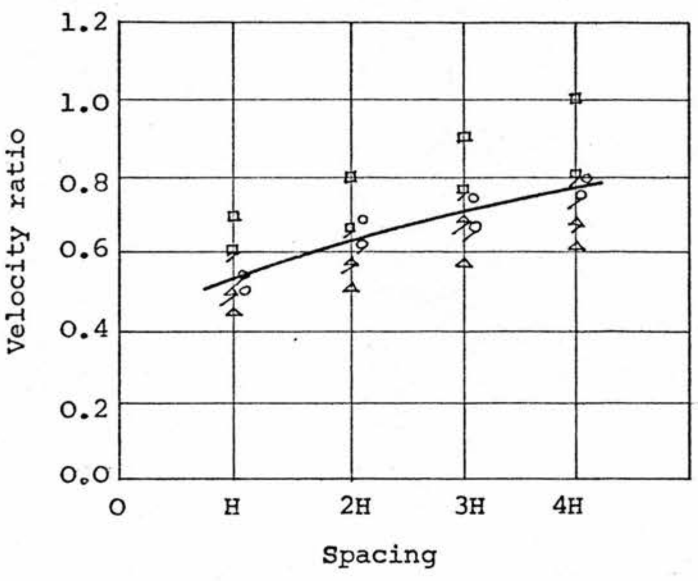


c. For block B_3

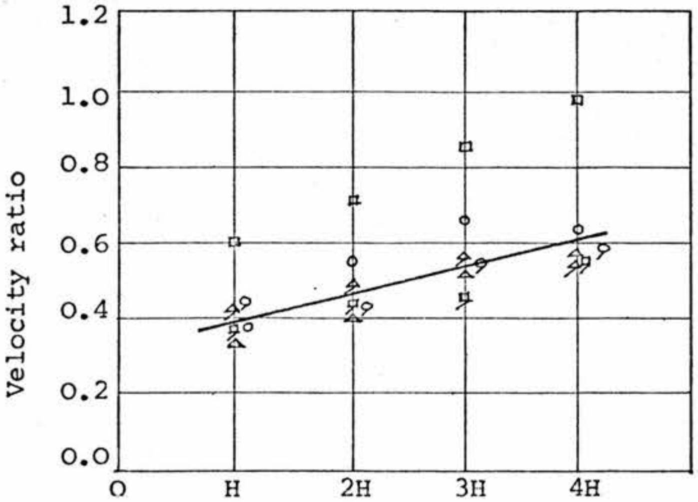
Fig. 32 (Cont'd)



d. For block B_4

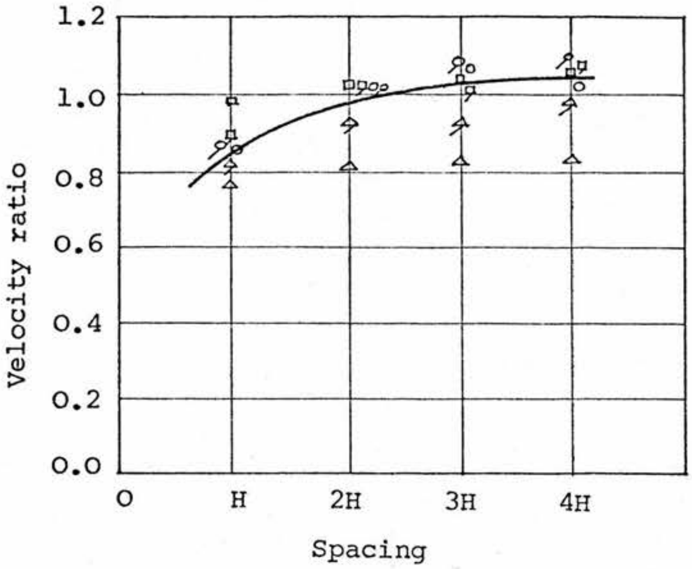


e. For Block B_5

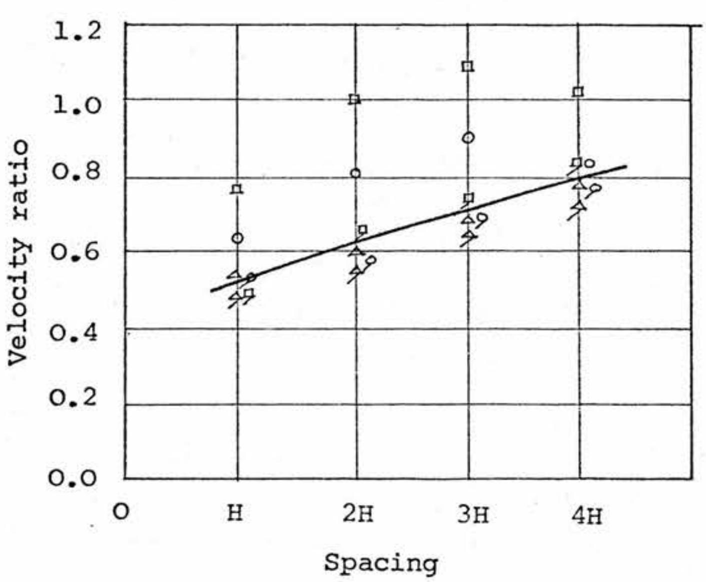


f. For Block B_6

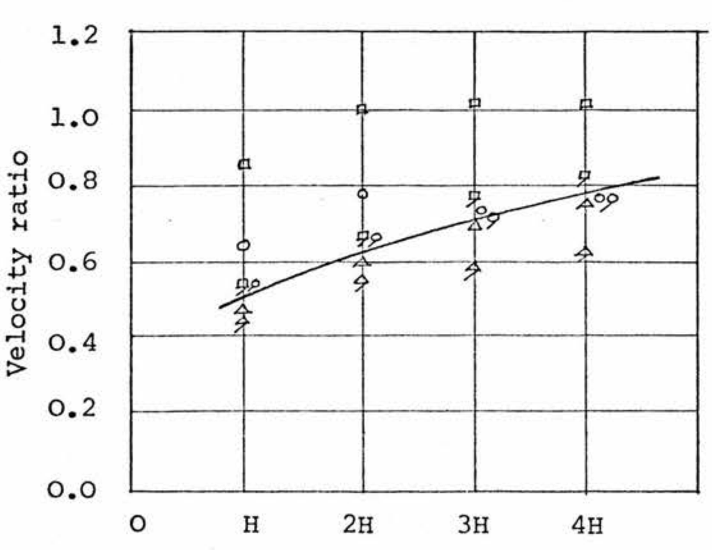
Fig. 32 (Cont'd)



g. For Block B_7



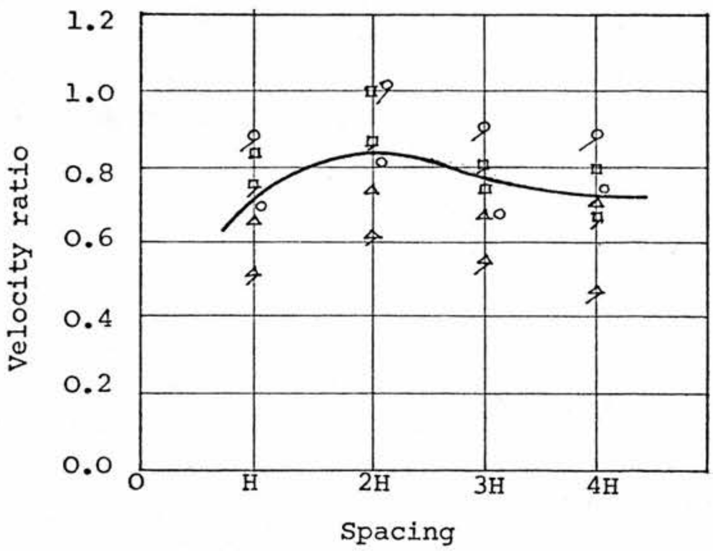
h. For Block B8



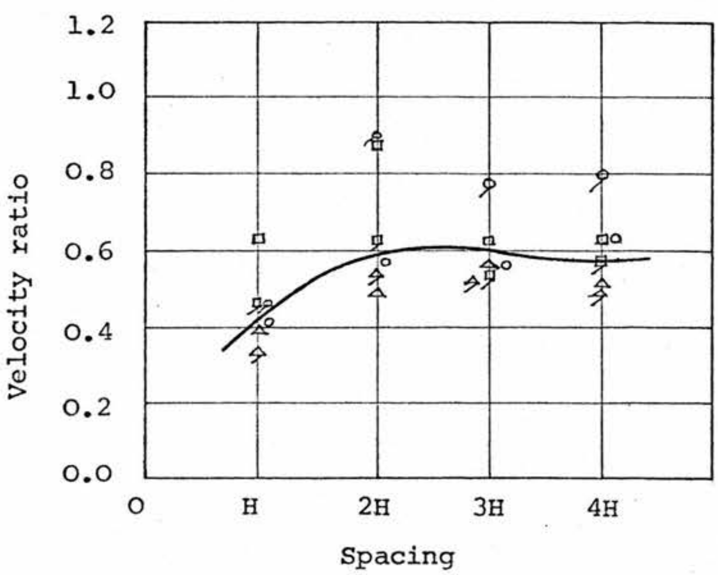
i. For Block B_9

Fig. 33.

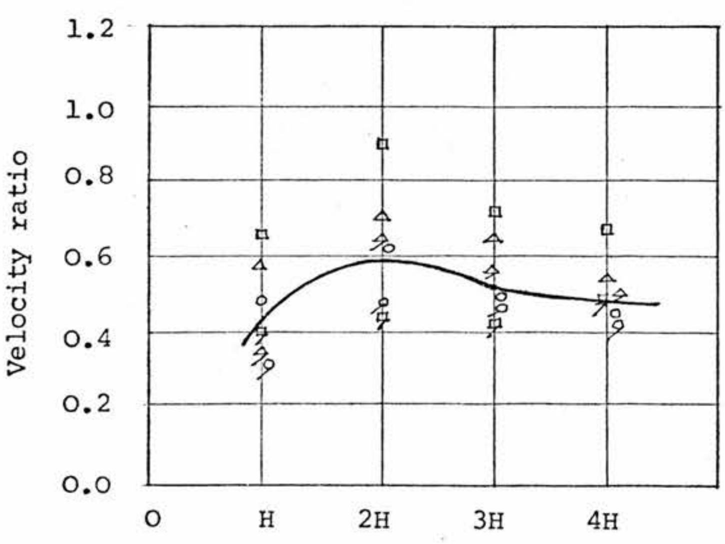
Measurements for blocks B_1 to B_9 in checker-board grouping with perpendicular wind direction.



a. For Block B_1

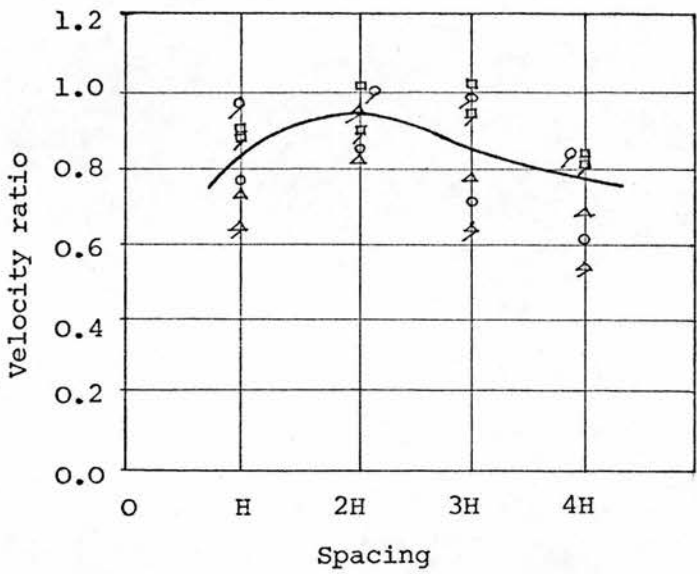


b. For Block B_2

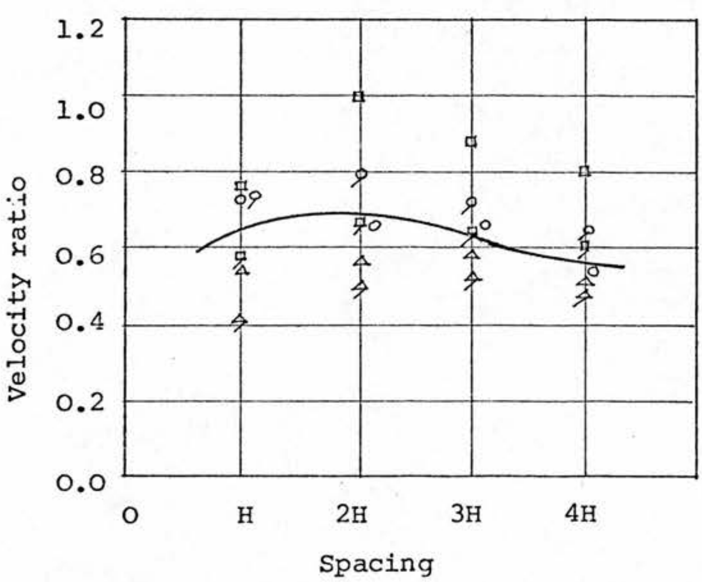


c. For Block B_3

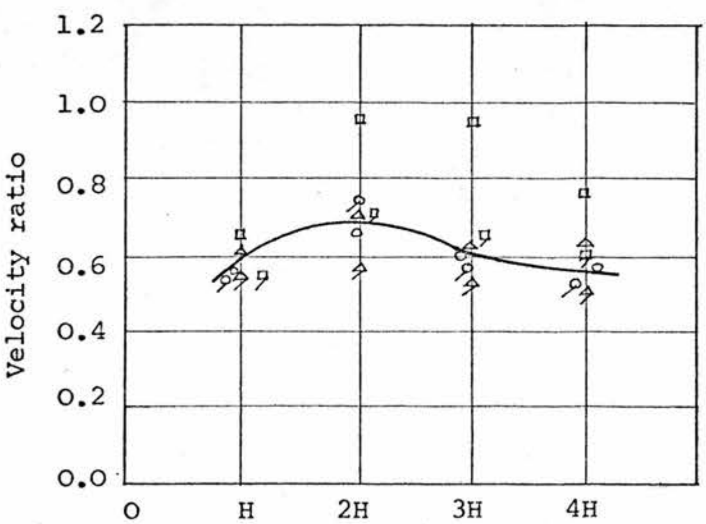
Fig. 33 (Cont'd)



d. For Block B_4

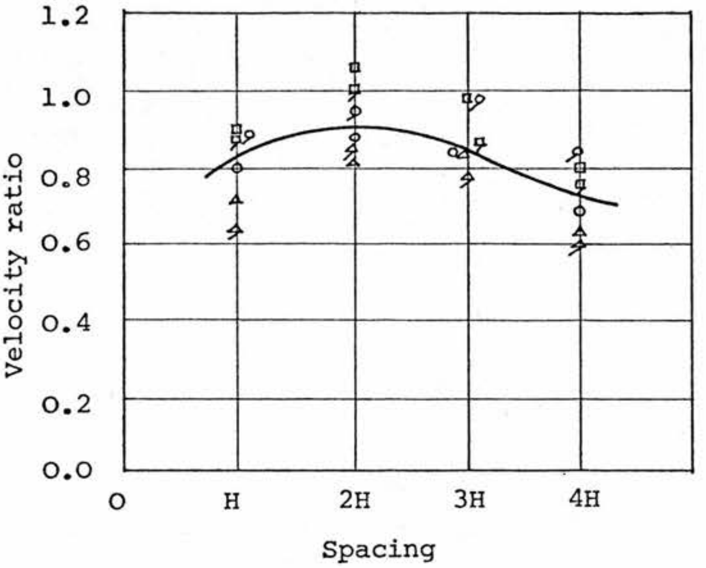


e. For Block B_5

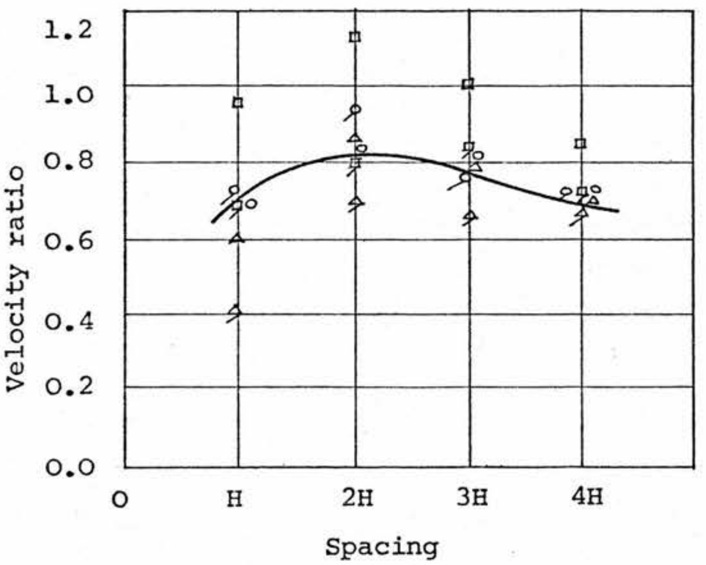


f. For Block B_6

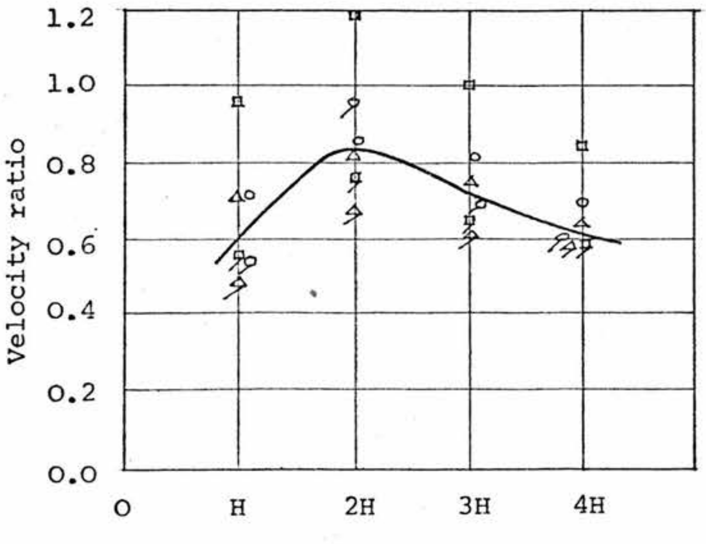
Fig. 33 (Cont'd)



g. For Block B_7



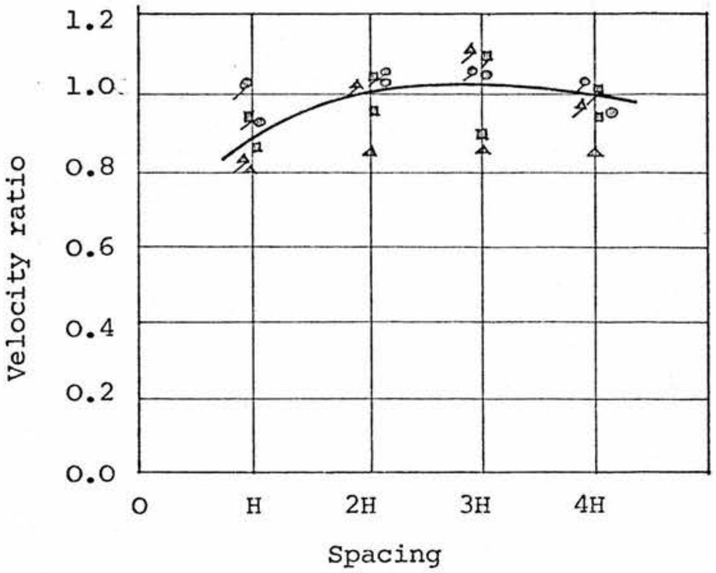
h. For Block B_8



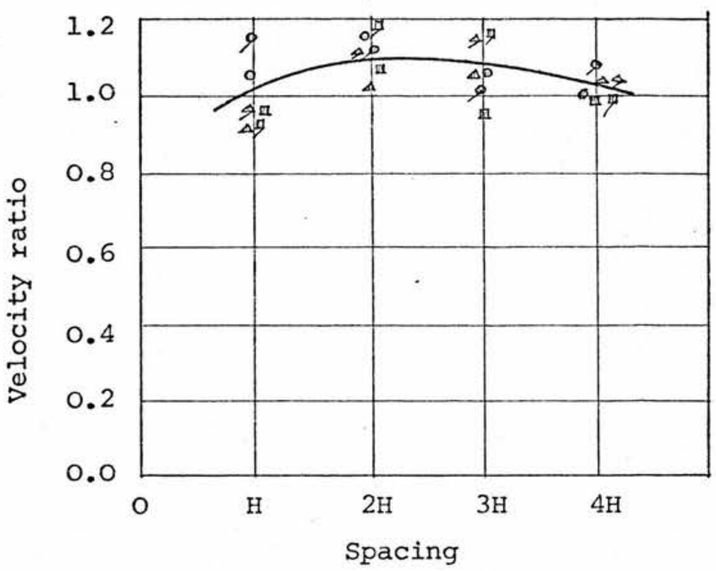
i. For Block B_9

Fig. 34

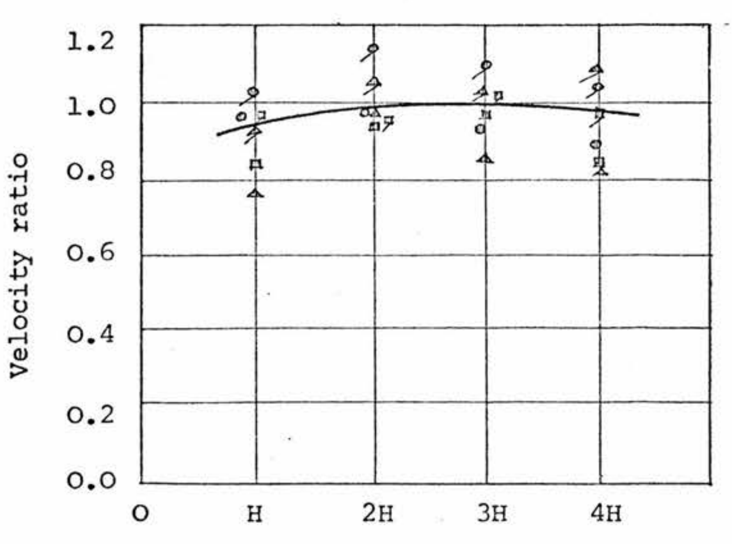
Measurements for Blocks B_1 to B_9 in grid-iron grouping with oblique (45^{o}) wind direction.



a. For Block B_1

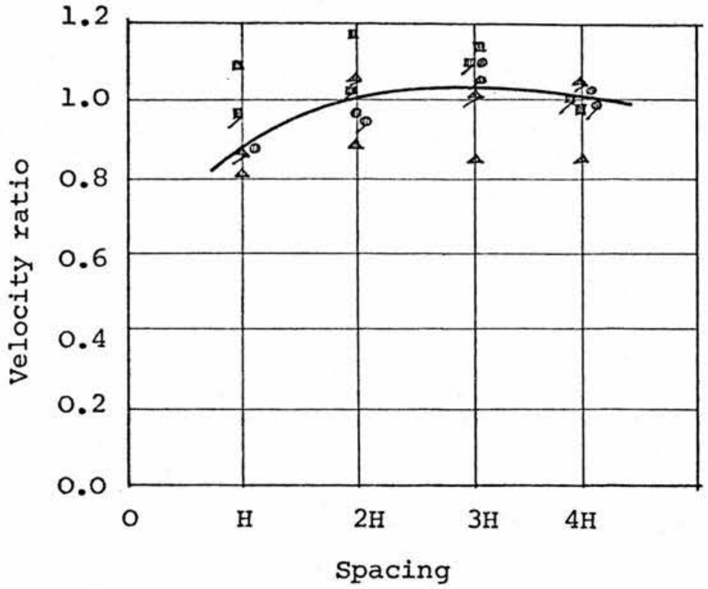


b. For Block B_2

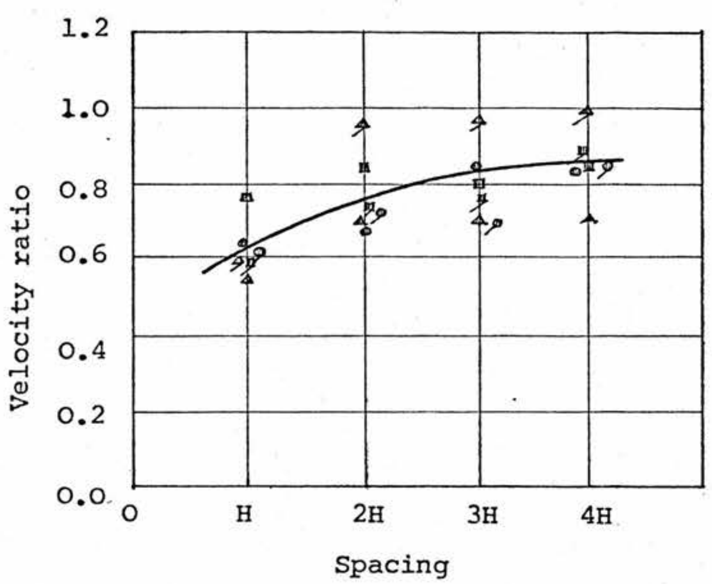


c. For Block B_3

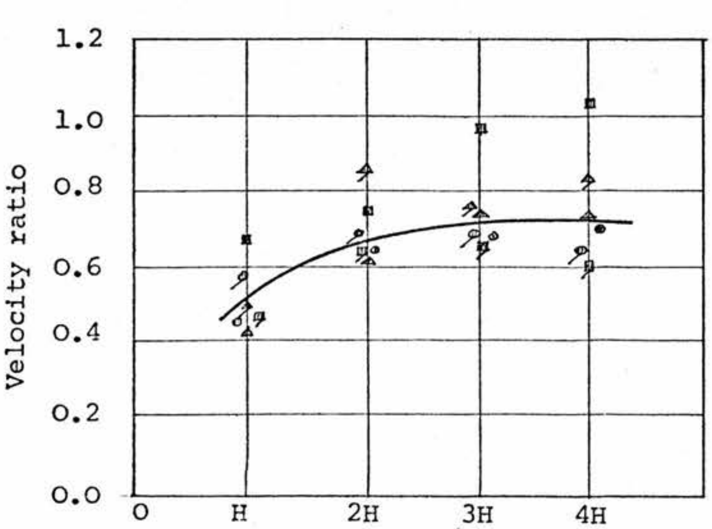
Fig. 34 (Cont'd)



d. For Block B_4

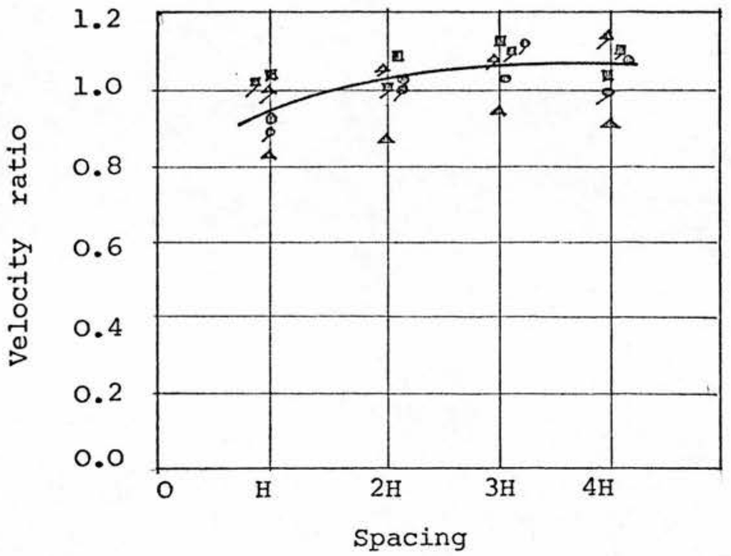


e. For Block B_5

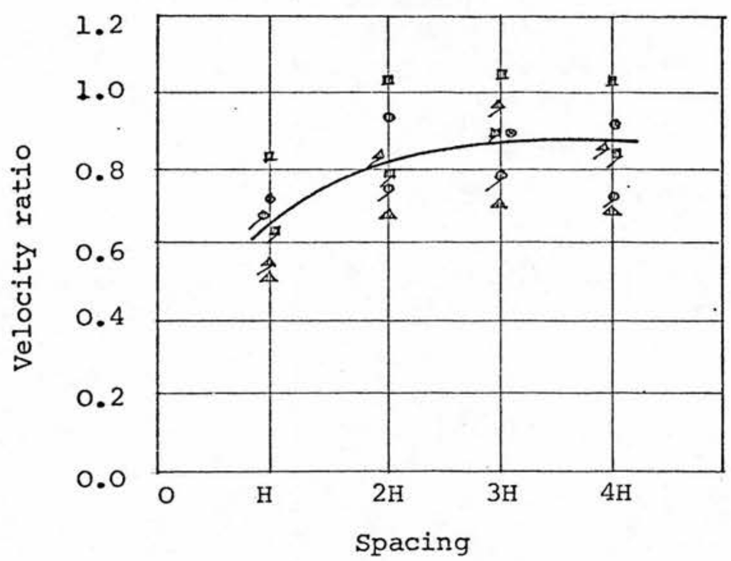


f. For Block B_6

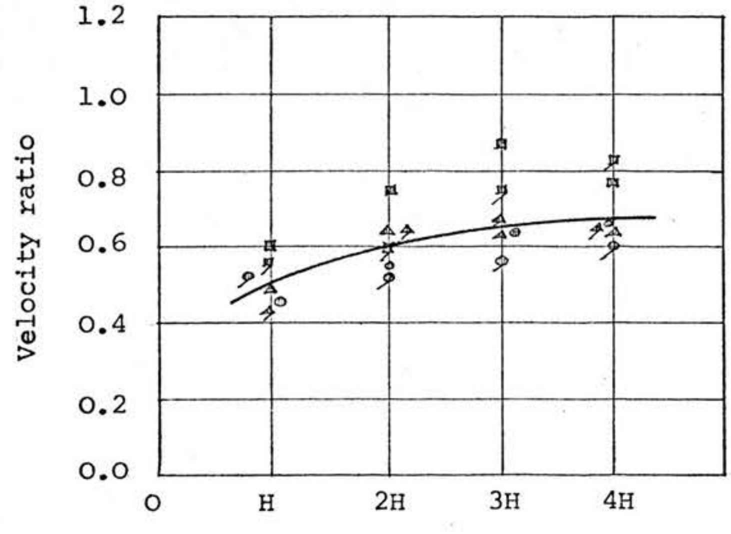
Fig. 34 (Cont'd)



g. For Block B_7



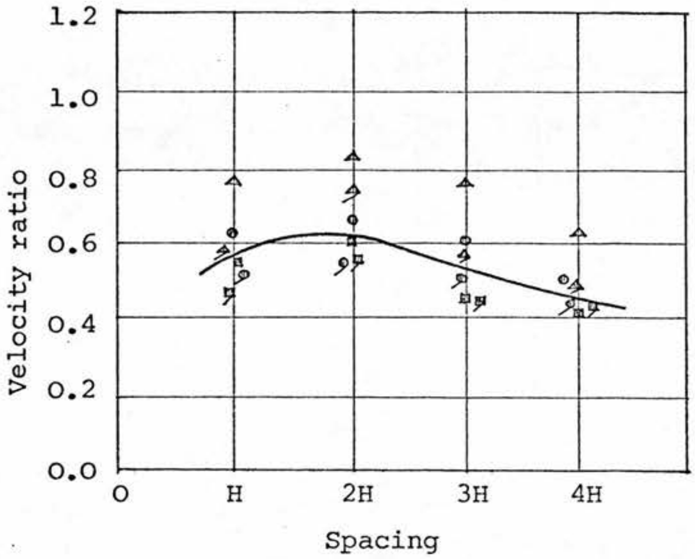
h. For Block B_8



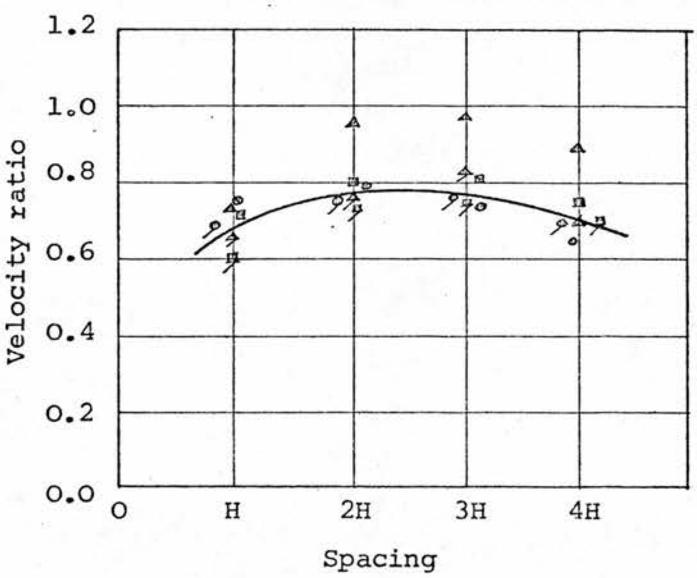
i. For Block B_9

Fig. 35.

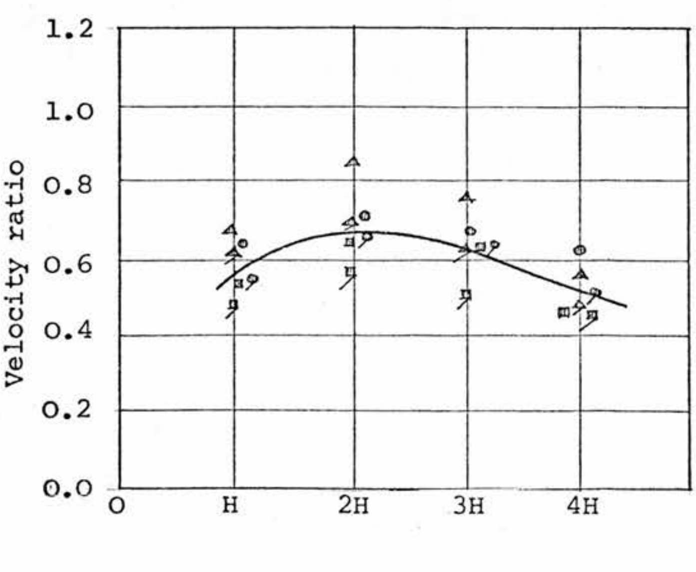
Measurements for Blocks B_1 to B_9 in checker-board grouping with oblique (45^{o}) wind direction.



a. For Block B_1

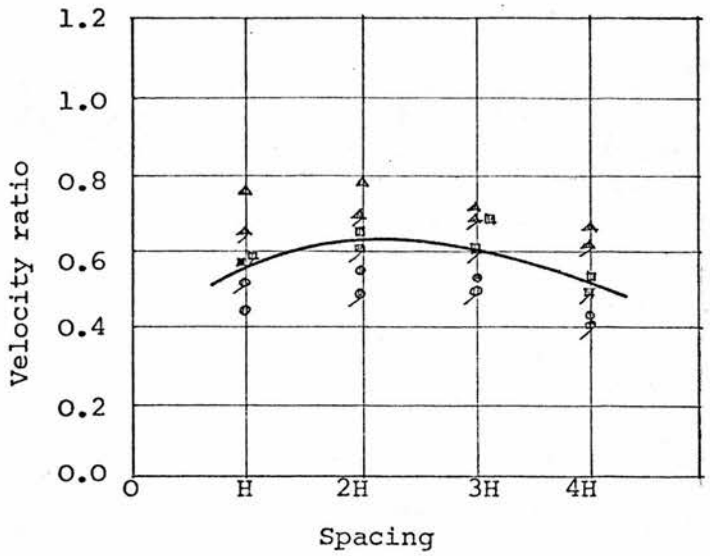


b. For Block B_2

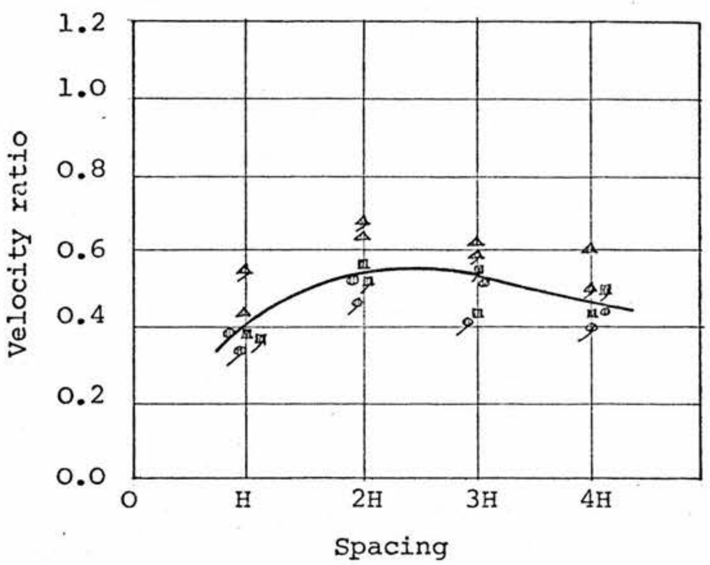


c. For Block B_3

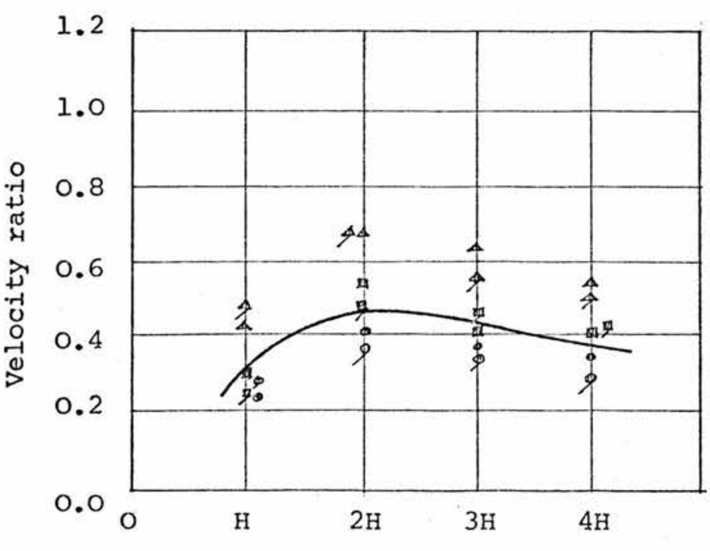
<u>Fig. 35</u> (Cont'd)



d. For Block B_4

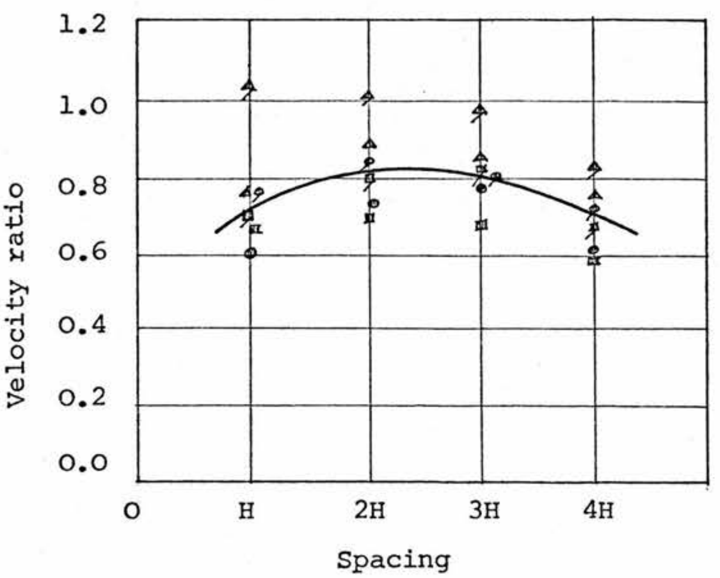


e. For Block B_5

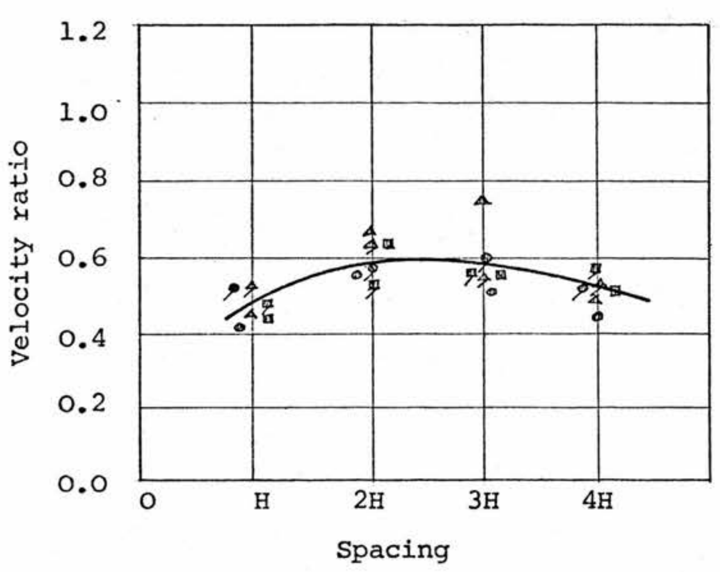


f. For Block B_6

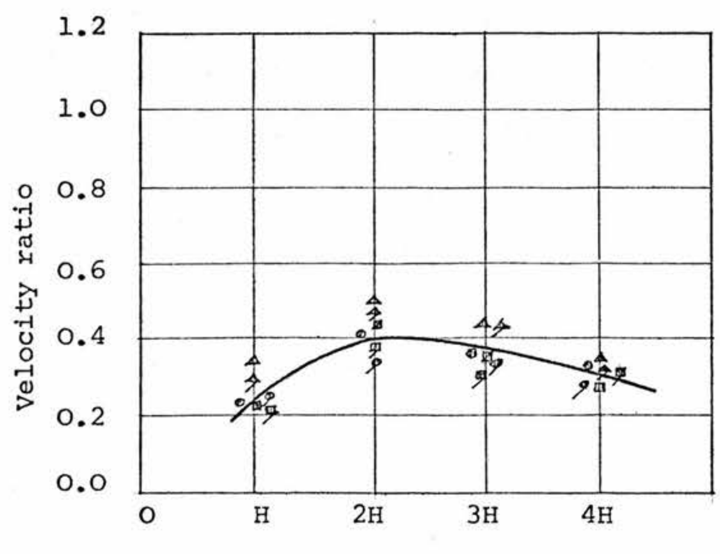
Fig. 35 (Cont'd)



g. For Block B_7

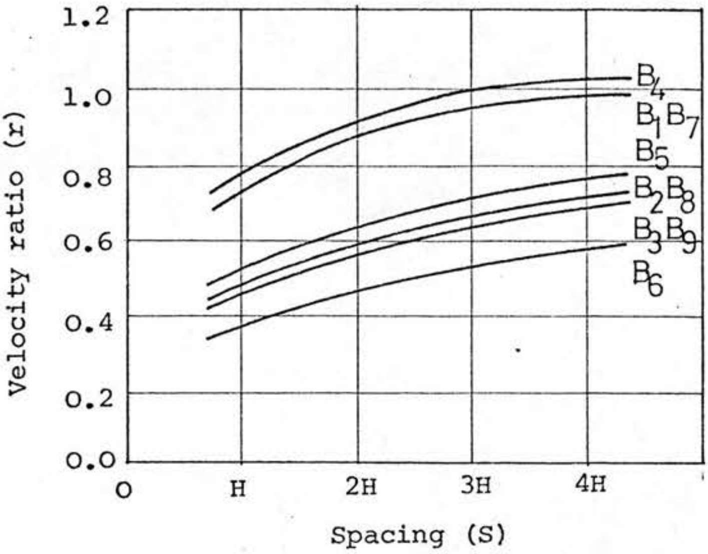


h. For Block B_8

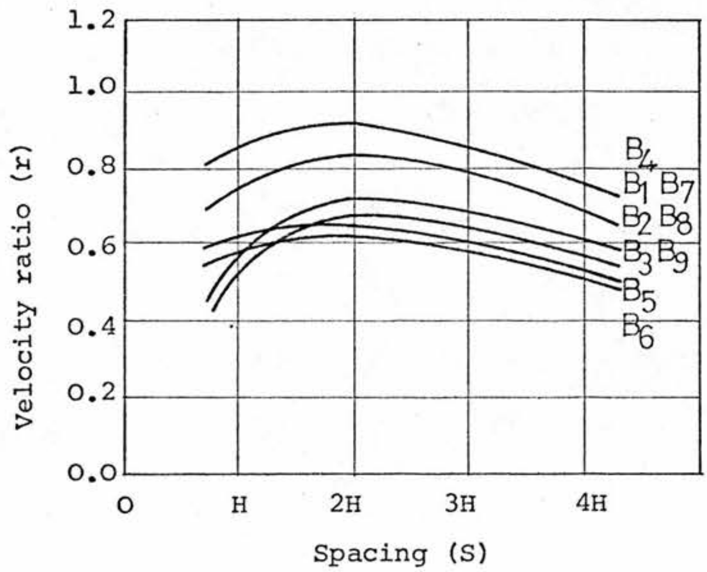


i. For Block B_9

Fig. 36
Summary of the preceding relationships.

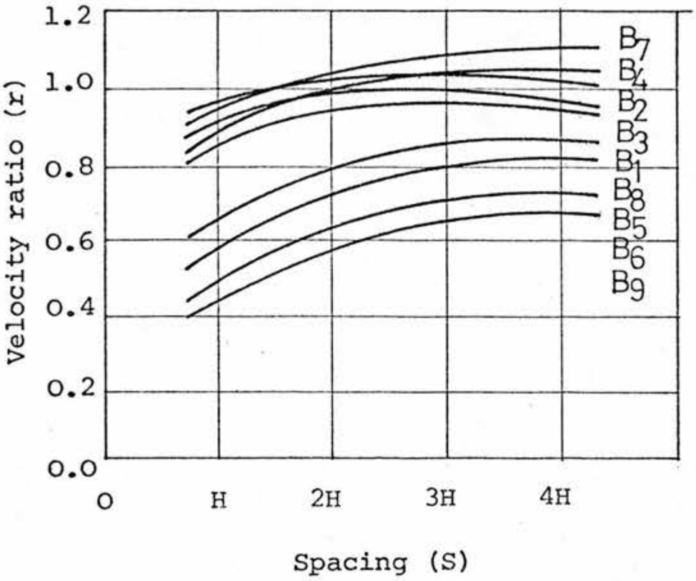


a. For grid-iron grouping with perpendicular wind direction.

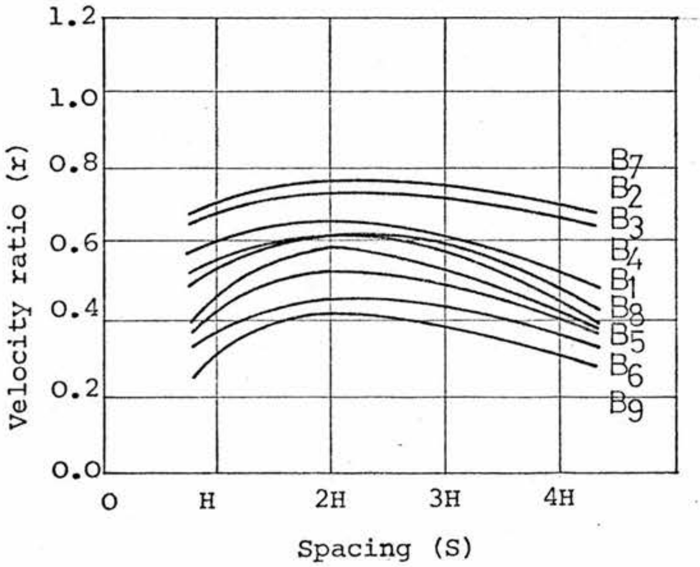


b. For checker-board grouping with perpendicular wind direction.

Fig. 36 (Cont'd)



c. For grid-iron grouping with oblique (45°) wind direction.



d. For checker-board grouping with oblique (45°) wind direction.

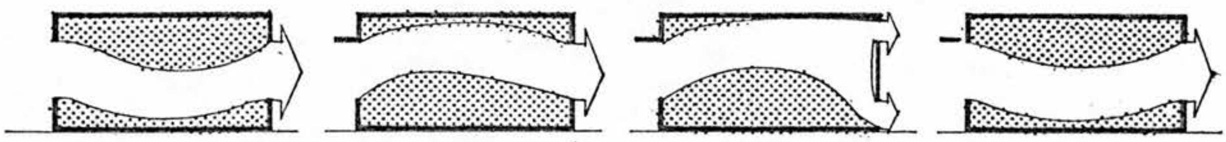
The results of the wind tunnel investigations summarized here are very interesting. It can be seen that for the checker-board grouping with both the perpendicular and the oblique (45°) wind directions, the velocity ratio curves for the different buildings in the grouping reach peaks at a spacing of about 2H, H being the height of the blocks. Of the two wind directions, the perpendicular wind produces better results in this grouping with the peak velocities at the inlets of the different buildings ranging between 70% and 90% of the prevailing wind velocity. With the oblique wind, the peak velocities achieved ranges between 40% and 80% of the prevailing wind velocity with most buildings having an inlet velocity of around 60% of the prevailing wind. Again the peak regions of the curves for both the wind directions are somewhat flat indicating that there is a degree of flexibility in the spacing of blocks in relation to the peak performance.

The grid-iron grouping on the other hand performs quite differently both under the perpendicular and the oblique winds. The velocity ratio for each block continues to increase with spacing up to a spacing of about 4H to 6H. With the oblique wind at a relatively short spacing of 2H, the velocities at the inlets of the different buildings ranges from 60% to 100% of the prevailing wind velocity, most buildings having a value of over 80%. With the perpendicular wind at a spacing of 2H, the velocities at the inlets are much lower, ranging between 50% and 90% of the prevailing wind velocity with most buildings having values of about 60% of the prevailing wind. From the summer ventilation requirements, these values can, however, be just adequate.

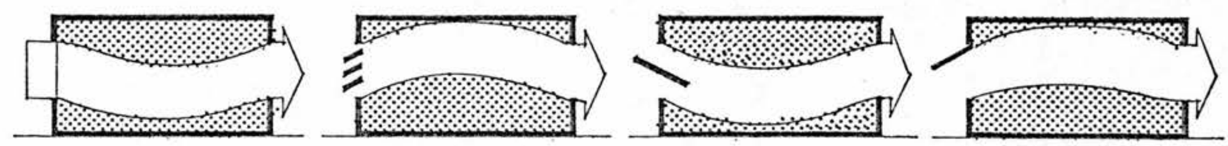
The results discussed here are quite significant particularly from the viewpoint of the requirements of high density and a degree of flexibility in the layout design. It is clear that adequate wind velocities at the inlets for summer ventilation requirements can be achieved at a relatively short spacing of 2H, thereby ensuring high densities in terms of the number of living units per hectare. For a grouping size much larger than the one tested or for a grouping pattern varying widely from the ones tested, the form-performance relationships are unlikely to be the same as the ones observed because wind flow is a particularly difficult phenomenon to generalize about. However, the approach adopted in the investigations seems worthwhile for further investigations involving more variations in the parameters of the form and the flow characteristics.

(ii) Effects on the degree of coverage of the occupied space by the incoming air stream due to variations in the geometric details of the protective features such as canopies, sashes and louvres.

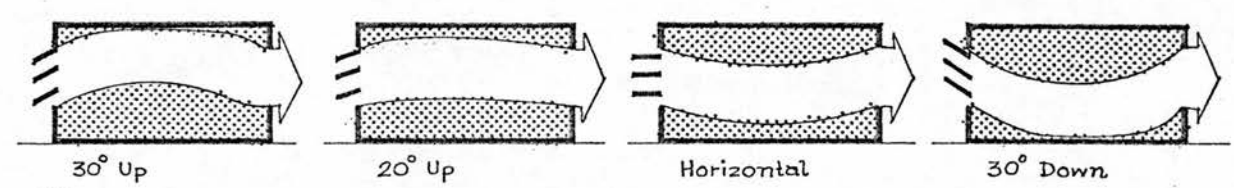
Projections and canopies used with inlet openings can alter the pressure build-up pattern on the inlet facade and thereby affect the direction of the air flow in the indoor space. Sashes and louvres can divert the inflowing airstream in accordance with their inclinations and because of the property of inertia, the air-mass tends to maintain the deflected direction irrespective of the location of the outlet openings (Caudill, Reed, 1952). These are illustrated diagrammatically in Figure 37.



Effects of canopies.



Effects of sashes.



Effects of louvres.

Fig. 37.

Although illustrations like these are commonly used in explaining the influence of the protective features (associated with the inlets) on the indoor air stream, the fact remains that these were observed in laminar flow and it is unlikely that a turbulent flow will produce similar patterns. In a turbulent flow, the incoming air will continue its turbulence and the whole of the indoor air mass will be involved in some kind of motion. The sashes and louvres can deflect the inflowing air according to their inclinations but the canopies will not have effects as pronounced as in the laminar flow.

PART 6

DESIGN APPLICATIONS OF THE FORM-PERFORMANCE RELATIONSHIPS.

6.1 A GENERAL DISCUSSION

Architectural design involves consideration of a number of complex requirements - technical, social, economic, climatic, psychological, aesthetic and so on all at the same time. Some of these requirements can be precise and quantifiable, while the others are subjective and not precisely measurable. Many of these requirements can be conflicting, for example high rise housing up to a height of 10 - 15 storeys can be more desirable from an economic view point compared to a low rise housing but from the social view point the latter is much more desirable. The job of a designer is to take into consideration all these requirements, measurable and non-measurable and sometimes conflicting with each other and achieve a balance of them in the proposed solution. The task sounds extremely complex but traditionally designers seem to have been handling these complexities in rather simple and individualistic ways without much regard to any systematic or 'scientific' design methods. In fact recent work has suggested that 'systematic design', promoted by the 'systematic design' movement of the recent past, was in any case based on a fallacious notion of scientific method and was psychologically and practically unworkable in real design (Hillier, Leaman, 1972).

The requirements which determine an architectural problem today are numerous and they are becoming increasingly complex. Designers are facing the problem of dealing with an increasing volume of data in the design process in order to be able to explore a range of possibilities for the proposed solution and evaluate the alternatives. It is primarily a question of optimization of the form in relation to the diversified requirements. Computers are being used as aids in this process although this practice is not widespread. The role of computers in architectural design is yet to be widely accepted by the profession and in certain situations, such as in the developing countries, widespread use of computers in design is often not feasible for economic as well as technical reasons. The vast majority of practising architects still prefer simplified design aids in the forms of tables, graphs and charts for easy assimilation and application in practice even if these are not rigidly accurate. In fact there is very little point in concentrating too much on the perfection of the design aids whilst the accuracy with which the physical properties of building materials and elements, boundary conditions and design weather data can be defined leaves much to be desired. Moreover, human beings, quite naturally, are capable of tolerating a degree of flexibility in the performances of the form.

The form-performance relationships established and illustrated in this thesis are intended to be used as design aids in incorporating climatic considerations in the design decisions from the viewpoint of human physical comfort in indoor spaces in a warm-humid climate, particularly in relation to high density urban housing in Dacca. The comfort requirements are expressed in the form of a 'comfort zone' (Fig. 7, Section 2.2.3). The comfort zone is defined in terms of the indoor DBT in ^{o}C, RH in %, air movement in m/s and radiative heat in W/m^2. It is not possible to synthesize these quantities into a single measure such as the net heat gain or loss by the indoor space without making a series of assumptions and resorting to complex and cumbersome mathematical treatments. Even if this is done which in any case will involve gross approximations, it will be extremely difficult to relate these heat gains or losses to such aspects or descriptors of the form as the orientations of the facades, configurations of the facades, solid-void relationships on the facades and so on, which constitute the vocabulary of form to a designer and it is in these terms that he conceives and develops his design. There is thus a need for using such measures for the performances of the form which can be directly and conveniently related to the various relevant descriptors of the form which the architect does concern himself with in the design process.

The measures of the performances of the form and the relevant descriptors of the form and their measures developed earlier in Part 4 of this volume are basic and appropriate in the sense that architects do think in those terms in the design process. However, difficulties of establishing precise relationships between the values of these measures of the performances and the indoor comfort requirements still exist. For example, depth of penetration of direct solar rays in an indoor space through an opening on a wall is hard to relate precisely to the DBT of the indoor air. Nevertheless, this constitutes an important consideration in the design process and from a practical viewpoint it is very often convenient and adequate enough to think in terms of excluding direct sunshine in a space or allowing penetration of it without too much concern for its precise impact on the indoor environment in terms of changes in the values of the comfort parameters. In other words, for practical design considerations, comfort requirements can be interpreted in terms of desirable values for the measures of the performances of the form as developed in this thesis. This can be done on the basis of an evaluation of the meteorological data on the given climate in relation to the comfort zone through discussion and reasoning. Complex and cumbersome mathematical treatments have been avoided because these are of little use in practice. In any case indoor environmental control by natural means, specially in 'open' buildings as are desirable in a warm-humid climate, has its limitations and because of the flexibility in comfort requirements the climatic design decisions are relatively uncritical as long as they are close to the right choice.

6.2 INTERPRETING COMFORT REQUIREMENTS FOR DACCA IN TERMS OF DESIRABLE VALUES FOR THE MEASURES OF THE RELEVANT PERFORMANCES OF THE FORM.

6.2.1 Evaluation of the meteorological data on the given climate in relation to comfort requirements:

In the absence of elaborate hourly data, the available meteorological data on the climate of Dacca may be suitably combined for plotting on the bio-climatic chart for Dacca. The resulting diagram will furnish the following information:

(i) Deviations of the prevailing conditions from the limits to the comfort zone. The degree of importance of the problem can be seen from this and the extent of the corresponding corrective measures estimated.

(ii) Whether any such deviations can be corrected by natural means.

The suitable combinations of the different meteorological data for plotting on the bio-climatic chart can be arrived at as follows:

(i) It is known that in the 24-hour cycle of an average day, the air temperature reaches its peak two to three hours past the mid-day (12 noon). The accompanying relative humidities are close to the lowest values. For this reason monthly mean maximum temperatures can be combined with the corresponding monthly mean minimum relative humidities and these combinations can be considered to be the representatives of the mid-day values.

(ii) Also it is known that the lowest air temperatures occur an hour or so before sunrise because immediately before sunrise the air temperature already begins to rise from reflected radiation from the atmosphere. Both the night time temperatures and the accompanying relative humidities closely follow the monthly average values. Therefore, monthly average temperatures can be combined with the corresponding monthly average humidities and the combinations can be considered to be the representatives of the night time values.

These combinations of the meteorological data for every month of the year have been plotted on the bio-climatic chart to give two sets of points for the two combinations (Fig. 38). Each point of a set corresponds to a month of the year and is marked with the corresponding Roman numeral. Points of each set are linked to produce two curves - the solid one representing the mid-day values and the broken one representing the night-time values. From the figure, the following observations can be made with regard to the summer and the winter times:

(A) Summer time: combinations of air temperature and relative humidity for the day as well as the night times 'above' the comfort zone for still air in the Fig. 38:

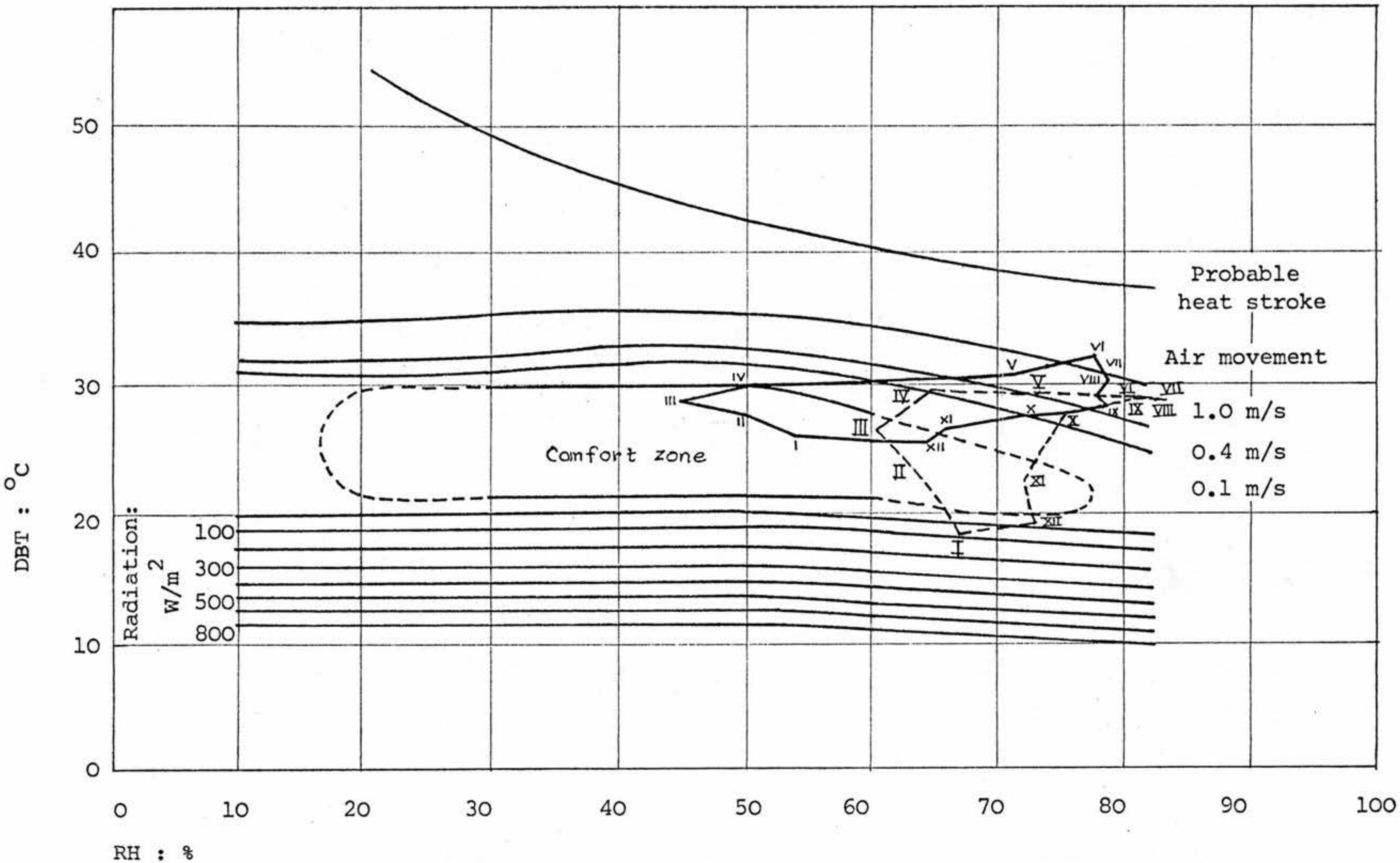


Fig. 38.

Combinations of met. data on the bio-climatic chart.

(i) The summer conditions prevail from the month of April to the month of October with the months of May, June, July, August and September representing the extreme of the prevailing conditions during the period.

(ii) The summer months call for air movement through the indoor space as given below in order to bring the prevailing conditions within or close to the comfort zone:

April	: Air movement at the rate of about 0.1 m/sec.
May to September	: Air movement at the rate of about 0.5 m/sec to 1.0 m/sec.
October	: Air movement at the rate of about 0.2 m/sec.

(iii) In the summer months, shading of the window areas must be maximized so that there is little or no penetration of direct solar radiation into the indoor space.

(iv) Insolation of the walls should be minimized or, in other words, shading on the surface of the envelope should be maximized to reduce solar heat gain through the fabric of the form.

(B) Winter time: combinations of air temperature and relative humidity for the day as well as the night times within or 'below' the comfort zone for still air in the Fig. 38:

(i) Winter prevails from the month of November to the month of March with the months of December, January and February representing the extreme of the prevailing conditions.

(ii) Through most of the winter period, conditions are quite within the comfort zone both in the day as well as in the night times. In December and January, conditions are within the comfort zone during the day time but get 'below' it in the evening and continue to remain so till about the following mid-morning. Consequently, heat energy is needed to restore comfort in the indoor space through this period of the winter days. The drop in the indoor air temperature in the evening and through the night can be counteracted by the delayed emission of heat from the inner surfaces of the form collected from the sun and stored in the fabric of the form during the day. Discomfort from low air temperatures in the morning can be alleviated by providing for penetration of the morning sun into the space.

(iii) Insolation of the walls should be maximized or in other words shading on the surfaces of the envelope should be minimized to increase heat gain by the fabric of the form to be stored and later released at night to raise the air temperature in the indoor space.

(iv) Flow of the prevailing cold wind through the indoor space must be restricted to the minimum level of ventilation requirements.

6.2.2 Formulation of a set of desirable values for the measures of the performances of the form, in relation to the comfort requirements:

For our purpose, performance of the form may be considered in two separate parts, firstly, in relation to the solar radiation and secondly, in relation to the air movement, i.e. the prevailing summer wind. Under these two different categories the appropriate measures for the relevant performances of the form as formulated earlier can now be specified in relation to the required days and the instants of the days as follows:

(A) Measures in relation to the solar radiation:

1. Duration of solar radiation received in an indoor space through an opening on a facade of the form on June 22 and December 22, the summer and the winter index days respectively.
2. Intensity of solar radiation received on the plane of a facade with opening on June 22 and December 22 at mid-morning, mid-day and mid-afternoon.
3. Width and depth (horizontally projected) of the beam of sunlight received in an indoor space through an opening on a facade on June 22 and December 22 at mid-morning, mid-day and mid-afternoon.
4. The degree of exposure, i.e. the area of the surface of a facade exposed to solar radiation on June 22 and December 22 at mid-morning, mid-day and mid-afternoon.
5. The extent of solar heat infiltration through the envelope expressed as a fraction of the incident solar radiation on its surface.
6. The decrement factor and the time-lag produced by the envelope.

(B) Measures in relation to the air movement:

1. Average velocity at the inlet of the incoming summer wind.
2. Degree of coverage of the occupied space by the air stream indoor.

The measures of the performances of the form enumerated above can now be considered one at a time on the basis of the evaluation of the given climate in relation to the comfort requirements and desirable values for each of these can be arrived at as follows:

(A) Measures in relation to the solar radiation:

1. Duration of solar radiation received in an indoor space through an opening on a facade of the form on June 22 and December 22, the summer and the winter index days respectively.

On the summer index day, the air temperature and the relative humidity combination for mid-day is well beyond the comfort zone for still air (Fig. 38). The night time conditions are also very close to this. It is of utmost importance to secure an air movement rate of about 0.5 - 1.0 m/sec. Moreover, all heat gains by the indoor space should be minimized during the summer months. Thus, the duration of direct solar radiation on a facade with openings should be minimized on the summer index day so that heat gain from direct radiation into a space is strictly restricted even when the openings are kept open for ventilation requirements.

On the winter index day, however, the given climatic conditions are well within the comfort zone throughout the day although at night the conditions fall slightly 'below'.the comfort zone requiring additional heat energy for maintaining comfort conditions indoors. This can be accomplished by maximizing the duration of direct solar radiation on a facade with opening on the winter index day so that direct solar radiation can be received in the indoor space throughout most of the winter days. From the Fig. 38 it can be seen that direct radiation in the indoor space is not really needed on the winter days when the conditions are well within the comfort zone. From experience, however, one knows that direct sunshine on winter days, specially in the morning and in the late afternoon, can be pleasant. Moreover, penetration of direct radiation in the indoor space enables the indoor fabrics of the form as well as the furnishings to gain solar heat and radiate back to the cooler parts of the indoor spaces. Also this heat gain can be stored in the fabric of the form to be released with a time-lag in the cold of the winter nights. Even if a facade with openings receives direct solar radiation throughout the winter days, one has the choice of restricting or cutting off completely its penetration in an indoor space by using curtains or venetian blinds.

2. Intensity of solar radiation received on the plane of a facade with opening on June 22 and December 22 at mid-morning, mid-day and mid-afternoon.

On June 22, the summer index day, there should ideally be no direct solar radiation on the plane of an opening. If, however, this is found unattainable because of the other design considerations, efforts should be made to achieve an orientation for the facade with openings, which will not only restrict the duration of direct solar radiation on the facade, but will also ensure a minimum intensity of radiation on the plane of an opening. On the winter index day (December 22), however, along with maximizing the duration of direct solar radiation on the plane of an inlet opening, the intensity of radiation received should be secured at a uniformly high level throughout the day so that heat gain in the indoor space from this source can be significant.

3. Width and depth (horizontally projected) of the beam of sunlight received in the indoor space through an opening on a facade on June 22 and December 22 at mid-morning, mid-day and mid-afternoon.

On June 22, the width and depth of the beam of sunlight received in an indoor space through an opening on a facade should be minimized, preferably reduced to zero, i.e. no direct sun penetration into the indoor space. On December 22, however, the width of the beam of sunlight received in an indoor space should be maximized, particularly in the morning and in the late afternoon periods and the depth of the penetrated beam of sunlight should be reasonable, say, at least about a third of the depth of the space. This will ensure a significant portion of the indoor space to receive the direct sun which in turn can result in significant heat gains by the indoor space.

4. The degree of exposure, i.e. the area of the surface of a facade exposed to solar radiation on June 22 and December 22 at mid-morning, mid-day and mid-afternoon.

On the summer index day, the exposure of the facades receiving direct solar radiation should be minimized. In other words, shaded areas on the surfaces of the facades should be maximized in order to reduce solar heat gain by the fabric of the form. This can be done by manipulating the configurations of the facades by advancing or receding vertical strips of a facade in relation to one another. Planning of indoor spaces of a residential block often requires this kind of staggering of spaces and this can be and needs to be accomplished in relation to the sun (and also to the prevailing wind).

On the winter index day, the exposure of the facades receiving direct solar radiation should be maximized, i.e. the shaded areas on the facades should be minimized to enhance solar heat gain by the fabric of the form. Even though the day time conditions in the winter days are quite within the comfort zone, the heat gained from the sun does not seriously affect the balance, particularly in a situation where the buildings are quite 'open'. On the contrary, this gain can be stored in the fabric of the form to be released at night when the air temperature tends to fall below the comfort level. This delayed heat emission from the inner surfaces of the envelope into the more controlled indoor environment with the doors and windows closed can be useful in the cold of late evenings and nights of the winter months.

5. The extent of solar heat infiltration through the envelope expressed as a fraction of the incident solar radiation on its surface.

The extent of solar heat infiltration through the envelope can be expressed in terms of the solar heat gain factor given by $\frac{q}{I} = 5\ U\alpha\%$ as stated earlier in the Section 5.1.3. For those parts of the envelope which receive intense radiations in the summer months, the solar heat gain factor should be quite low. For the parts which receive direct sun in the winter months only, its value can be higher. It is difficult to specify definite values for such a factor when its impact on the indoor environment in terms of precise changes in the values of the comfort parameters are difficult to establish. However, from a knowledge of, and experience in, the range of possible materials and constructions (with their respective values of U and α) in a particular situation, it is possible to estimate a desirable value for this quantity. Koenigsberger et al. (1974, p.74) suggest that for a warm-humid climate, its value should not exceed 4%. This seems reasonable for those parts of the envelope exposed severely to the summer sun. For those parts which receive direct sun in the winter days only, the values may exceed this figure.

6. The decrement factor and the time-lag produced by the envelope.

For those parts of the envelope receiving direct solar radiation in the summer months, particularly in the summer afternoons, both the decrement factor and the time-lag should be kept low so that the indoor temperature is low and the phase shift between the outdoor and the indoor temperature cycles is less. This will ensure that discomfort in the summer nights will not be enhanced by delayed emission of heat from the fabric of the form into the indoor space. On the other hand those parts of the envelope which receive direct solar radiation in the winter months only may be allowed higher decrement factors and longer time-lags so that delayed heat emission from the inner surfaces of the envelope can be useful in the cold of late evenings and nights in the winter months.

(B) Measures in relation to the air movement:

1. Average velocity at the inlet of the incoming summer wind.

In the summer months, the air temperature and the relative humidity combinations are well outside the comfort zone for still air (Fig. 38) and air movement at the rate of about 1.0 m/s is required to restore comfort conditions in the indoor space. Although velocities in the different areas of the occupied space in a building are extremely difficult to predict, for practical purposes the indoor air velocity requirements can be expressed in terms of the desired average velocity of the incoming air stream at the inlet provided that the inlets are suitably located in relation to the occupied zone and the flow is directed towards the occupied area. Prevailing wind velocities in the warm-humid tropics are typically low, about 4 - 5 m/s and in practice it is desirable to maximize the velocity at the inlet even though at times it may result in slightly higher indoor air velocities than the required values. In fact this will be all the more desirable because higher air speeds themselves induce cooling and enhance the feeling of comfort at high temperatures and relative humidities. In the winter months, the prevailing cold wind, blowing from a different direction, may be kept out by closing down the windows on that side of the building.

2. Degree of coverage of the occupied space by the air stream indoor.

From the summer comfort viewpoint, the rate of air movement in the occupied zones of the indoor space is important. The inlet for the summer wind should be such that the incoming air stream is allowed to flow close to the floor thereby maximizing the coverage of the occupied space. This will also achieve a higher average velocity in the occupied zones. In the winter months, however, the flow through the indoor space needs to be restricted to minimum levels.

6.3 ESTABLISHING DESIRABLE VALUES FOR THE MEASURES OF THE DESCRIPTORS OF THE FORM.

6.3.1 Enumeration of the relevant descriptors of the form and review of the relative importance of the climatic factors (solar radiation and the prevailing wind) in dictating the values of their respective measures:

The appropriate descriptors of the form formulated earlier (in Part 4) can now be considered one at a time and the relative importance of the two climatic factors under consideration in dictating the values of their measures can be reviewed as follows:

1. Orientation of the facade with inlet openings:

The orientation of a facade is important both from the viewpoints of solar radiation and the prevailing wind. From the study of human physical comfort and comfort requirements (in Part 2), it is clear that the rate of air movement is a critical factor in a warm-humid climate. While solar radiation, particularly its exclusion from an indoor space can be dealt with in many ways other than through manipulation of the orientation of the facade with openings, the prevailing wind can not be dealt with for effective cross ventilation without securing the right orientation for the facade with openings in relation to the prevailing wind. It will be ideal if the best orientation for the sun turns out to be the best for the prevailing wind also. In the case of a conflict, a balance has to be reached. In such a situation the prevailing wind consideration has to be given preference as far as orientation of a facade with the inlet openings is concerned. Solar entry can be controlled by detailed design, but there is no way of generating wind movement by details.

2. Solid-void relationships on the facade with the inlet openings:

This descriptor of the form bears similar relationships with the two climatic factors as discussed above. It will be ideal again if the requirements dictated by the two climatic factors in terms of the desirable values for the measures of the descriptor are identical or close to one another. However, for the same reasons as before, the prevailing wind considerations will take preference over the solar radiation considerations in the case of a conflict.

3. Configuration of a facade:

The building facades under consideration are of two distinct types - the solid ones and the ones with openings. For a facade with inlet openings (for the winter sun and the summer wind), the configuration will be dictated both by the sun and the prevailing wind. In cases having conflicting requirements, the summer wind considerations will demand preference because adequate air movement in the indoor space is much more critical for the summer months than sunshine in the indoor space in winter when the thermal environment, in any case, is within or very close to the comfort zone. For the solid facades and the facade with outlet openings (for the summer wind), the configurations will be dictated entirely by solar radiation considerations because these are of little or no relevance to indoor cross ventilation in summer.

4. Thermo-physical properties of the surface and the fabric of the envelope:

Indoor air movement, particularly cross ventilation through an indoor space, is dictated primarily by the geometric properties of the form. The indoor thermal environment (which includes indoor air movement) is dictated very largely by the solar heat gain through the fabric of the form which in turn depends on the thermophysical properties of the surface and the fabric of the envelope. Thus the thermo-physical properties of the surface and the fabric of the envelope will be dictated by solar radiation considerations.

5. Grouping pattern and spacing of the building blocks:

Air flow in a built form, both around and through buildings are very strongly influenced by grouping pattern of the building blocks and spacing between them as is well known and observed once again in the wind tunnel simulations undertaken in the course of the current investigations. In a warm-humid climate where cross ventilation through the indoor spaces in the summer months is a very critical factor indeed, the grouping pattern of the building blocks and spacing between them will be dictated predominantly by the summer ventilation considerations. However, considerations of solar radiation can also come in in connection with preventing casting of shadows by one row of blocks over the other in the winter days. In the summer months, the sun's traverses across the sky hemisphere are much higher and consequently the shadows cast by buildings are much shorter throughout most of the day. It is thus not feasible to achieve any significant shadow casting effect by one row of blocks over the other which would have been desirable in the summer months without bringing the rows very close to each other at the expense of the summer ventilation requirements.

6. Controlling features at the inlet (canopies, sashes and louvres).

These are dictated both by the sun and the prevailing wind. The use of these features in controlling penetration of direct solar radiation into the indoor space and deflecting the incoming air stream at the inlet is well known. If the orientation of the facade with inlet openings from ventilation considerations invites undesirable direct solar radiation on the openings, then the openings can be provided with these features designed in relation to the sun through simple geometrical analysis. At the same time considerations for favourable deflection of the incoming air stream at the inlet can be incorporated in these features. For an orientation where the question of sun control does not arise, these features can still be needed for suitable deflection of the incoming air at the inlet.

6.3.2 Establishing desirable values for the measures of the descriptors of the form:

From a knowledge and understanding of the desirable values for the measures of the relevant performances of the form as formulated in the Section 6.2.2, it is possible to use the form-performance relationships developed and illustrated in this thesis to determine desirable values for the measures of the descriptors of the form. This, for each of the relevant descriptors of the form, can be done as follows:

1. Orientation of the facade with inlet openings:

From the Fig. 18 in Section 5.1.3 expressing variations in the duration of solar radiation received on a facade corresponding to variations in its angle of orientation, it can be seen that the critical requirement of minimum insolation on the facade with opening on the summer index day (June 22) can be achieved by securing an angle of orientation of 180°, measured clockwise from the north direction, for the facade with inlet openings. The figure shows further that this orientation also satisfies the desirable but not so critical requirement of maximum insolation on the winter index day (December 22) for the facade with inlet openings.

From the Figure 20 expressing variations in the intensity of solar radiation received on the plane of a facade corresponding to the variations in its angle of orientation, it can be seen that an angle of orientation of 180° for the facade will ensure receipt of the least amount of radiation on the summer index day while securing a high and more or less uniform receipt of radiation on the winter index day.

Again from the Figure 36 in Section 5.2.3 expressing variations in the velocity-ratio (r) at the inlet corresponding to variations in the orientation, grouping pattern and spacing of the building blocks, it can be seen that the checker-board grouping with perpendicular wind direction or the grid-iron grouping with oblique wind direction (Fig. 29) will secure the best possible ventilation situations for all the buildings in a group at close spacings (about 2 times the height of the blocks) under the given conditions. In the case of Dacca, since the prevailing wind is from the south/south east, the orientation of the building blocks (i.e. orientations of the facades with inlet openings) can be satisfactory between the values of 135° and 180° of the angle of orientation (measured clockwise from the north direction) with appropriate grouping of the blocks.

Thus, on the basis of the solar radiation and the prevailing wind considerations, the optimum value of the angle of orientation for the facade with inlet openings can be accepted to be 180°

measured clockwise from the north direction. From the prevailing wind considerations, however, the angle of orientation for the facade with openings can be as less as 135^{o}. But as can be seen from the Figures 18 and 20 in Section 5.1.3, such a deviation from the optimum value would invite long duration (up to noon) and high intensities of radiation on the facade on the summer index day. However, slight variations, up to 10 - 15 degrees less than the optimum value, would not produce much adverse effect in relation to the duration or intensities of the summer sun received on the facade as is evident from the Figures 18 and 20.

Once the orientation of the facade with inlet openings is fixed, the orientations of the other three facades are also fixed because the buildings under considerations are rectilinear blocks. Thus for the optimum orientation of 180^{o} from the N-direction for the facade with inlet openings, the facade with outlet openings will have an angle of orientation of 0^{o} and the two solid facades will have angles of orientation of 90^{o} and 270^{o}, all measured clockwise from the north direction. The rest of the analysis concerning the remaining descriptors of the form will be carried out assuming these orientations for the building facades. Needless to say that for any other combinations of orientations within the acceptable range, the analysis will follow the same general course.

2. Solid-void relationships on the facade with inlet openings:

From the Fig. 23a in Section 5.1.3 expressing variations in the width of the penetrated beam of sunlight in the indoor space corresponding to variations in the angle of orientation of the facade with inlet openings, it can be seen that an angle of orientation of 180^{o} for the facade with inlet openings will ensure more or less uniform widths of the penetrated beam of sunlight through most of the day, the average value of the widths at the various instants of the day being very close to the maximum possible value at any given instant of the day on the winter index day. Also it is clear that the maximum possible width (w) of the inlet openings will ensure the maximum possible width of the penetrated beam of sunlight in the indoor space.

From the Figure 23b expressing variations in the depth (horizontally projected) of the penetrated beam of sunlight corresponding to variations in the orientation of the facade with openings, it is clear that an angle of orientation of 180° will ensure more or less uniform depths of the penetrated beam of sunlight in the space at the different instants of the day on the winter index day. The average of the depths for this orientation is about 0.9h, h being the height of the opening. This value is greater than the average value for any other orientation. The average depth of an indoor space is about 4 metres. Therefore for a desirable sun penetration into the indoor space on winter days (about one-third of the depth of the space as stated earlier), we must have,

$$0.9h = \frac{1}{3} \times 4 \text{ metres}$$

or $h = 1.5$ m (approximately)

Thus, from the consideration of the winter sun penetration, the desirable dimensions for an inlet opening will be about 1.5m (height) by the entire width of the facade at that end of the indoor space.

Also from the prevailing wind considerations, the maximum possible widths for both the inlet and the outlet openings are desirable. Givoni's measurements indicate that the average internal air velocity increases with a simultaneous increase in the inlet and the outlet sizes (Givoni, 1962, p.49).

As regards location of openings on the facades, three distinct possibilities are examined here as in the Figure below (Fig. 39).

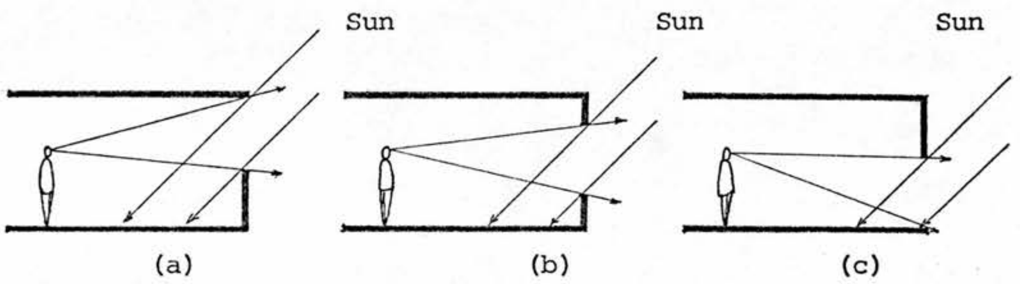


Fig. 39

When the opening is in the top-third of the height of the facade as shown in (a), vision is directed towards the bright sky even when the occupant is deep in the space thereby inviting serious glare problems. Moreover, the normal view of the outside world is drastically cut off. Also coverage of the occupied space by the inflowing summer wind will be poor even if some kind of deflector is used.

When the opening is in the bottom-third of the height of the facade as shown in (b), vision is directed towards the ground. This eliminates glare problem from the bright sky altogether and at the same time ensures very good coverage of the occupied space by the incoming summer wind. But this also introduces the problems of poor day lighting in the indoor space and poor outdoor view.

The arrangement shown in the diagram (b) where the opening is located mostly in the middle-third of the height of the facade offers a suitable balance between the two extremes with the following advantages:

(i) It directs the view more or less horizontally thereby reducing glare from the bright sky.

(ii) It provides a good 'looking out' situation.

(iii) It keeps the window at a convenient operational level.

(iv) The coverage of the occupied zone by the incoming summer wind can be satisfactory.

Therefore, the desirable vertical location for the centroids of the openings will be in the lower middle-third of the height of the facade in relation to the indoor spaces. This is in agreement with the findings of Ishwar chand and Krishak, N.L.V. (1969, p. 375-78) of the Central Building Research Institute, Roorkee, India.

3. Configuration of a facade:

It has been accepted that the facade with inlet openings (for the winter sun and the summer wind) will have the optimum angle of orientation of 180° measured from the N-direction. Therefore, because of the rectilinear geometry of the building blocks, the other three facades will have angles of orientation of 0°, 90° and 270°, all measured clockwise from the north direction. In other words, the four facades will face the north, the east, the south and the west directions. We can now study the required configuration characteristics for these facades taking one facade at a time as follows:

(i) The facade with an angle of orientation of 0° (i.e. the north facade):

This is the facade with outlet openings for the summer wind. It has already been stated that the configuration of this facade is irrelevant from the summer cross ventilation considerations. However, from solar radiation considerations this is important. From the Table 5 (in section 5.1.3) expressing the values of the horizontal and the vertical shadow angles on the plane of a facade corresponding to different orientations of the facade, it can be seen that on the summer index day (June 22) at mid-morning and mid-afternoon, the horizontal shadow angle θ for this facade is 77° measured clockwise and anti-clockwise respectively from the direction of orientation. Table 8 (in section 5.1.3) expressing the shadow characteristics on a facade (values of x and y in Fig. 24, section 5.1.3) in terms of the depth of staggering (d) in the facade for different orientations of the facade, it can be seen that the width of the shadow cast by an advanced strip on the adjacent rear strip of the facade will be given by $x = 4.33d$ at mid-morning and mid-afternoon of the summer index day. This means that any staggering on the facade will have profound shadow casting effects on the rear strips in the morning and/or in the afternoon periods of the summer days, there being no direct radiation at mid-day on the facade. Thus parts of the facade, particularly the openings on it can be protected from the morning and/or the afternoon sun in the summer days by manipulating the staggering on the facade. The figure below (Fig. 40) illustrates possible interactions between the configuration of the facade and the morning and the afternoon solar radiation in the summer days.

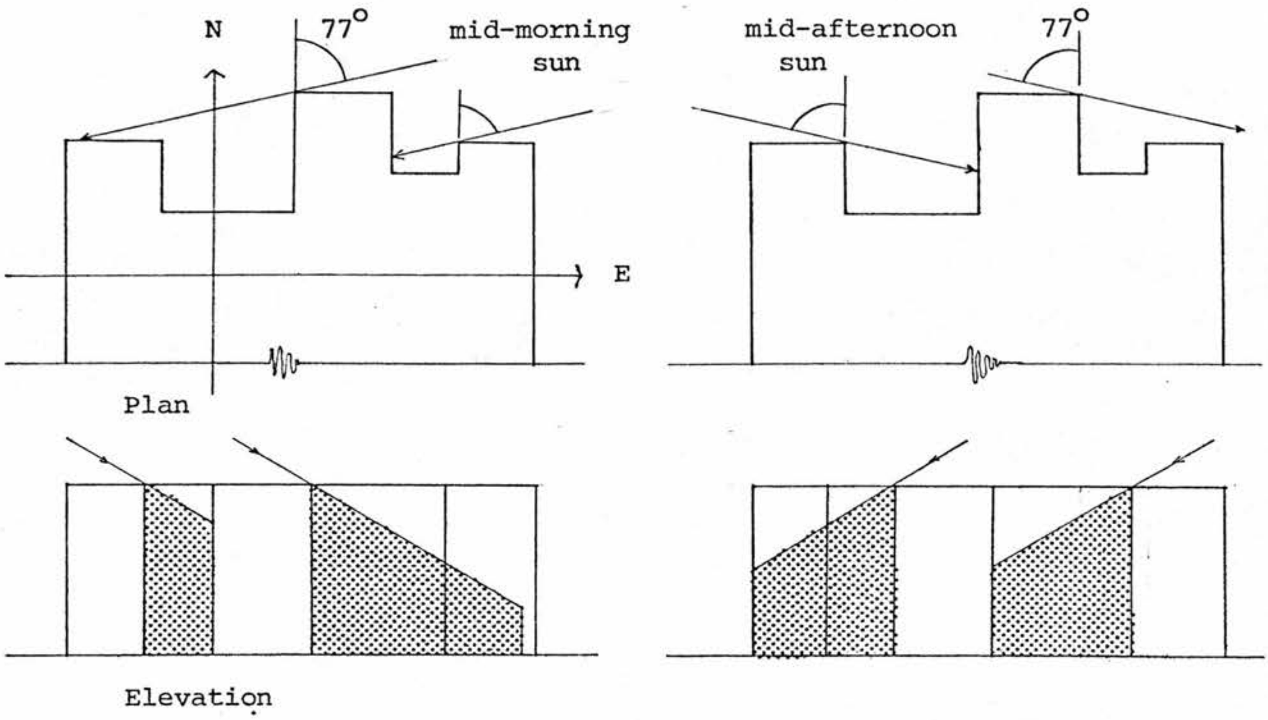
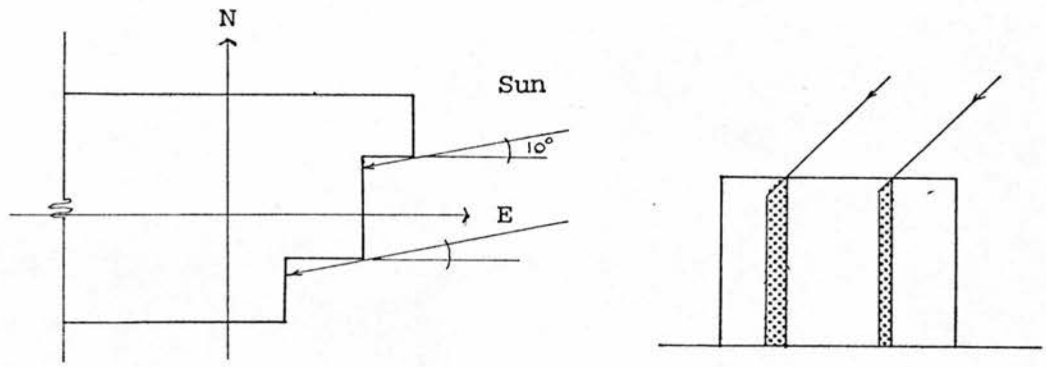


Fig. 40.

(ii) The facade with an angle of orientation of 90° (i.e. the east facade):

This facade will be a solid one. From the Table 5 (in Section 5.1.3) it can be seen that on the summer index day at mid-morning, the horizontal shadow angle for the facade is 10° measured anti-clockwise from the direction of orientation. This means that the facade should be staggered towards the south-east as shown in the Figure below (Fig. 41) to achieve shadow casting effect by one advanced strip on the adjacent rear strip in the summer mornings.

From the Table 8 (Section 5.1.3), it can be seen that for this facade on the summer index day at mid-morning, the width of the shadow on a rear strip will be given by $x = 0.18d$ only. This means that for practical values of depths of staggering d, the shadow casting effect on this facade in the summer mornings can not be that significant.



Plan

Elevation

Fig. 41.

However, it can be of some advantage if greater depths of staggering can be secured in this facade.

Again, from the Table 5, it can be seen that on the winter index day at mid-morning the horizontal shadow angle θ for this facade is 48° measured clockwise from the direction of orientation. This means that for the nature of configuration stated above, the facade will have full exposure to direct solar radiation in the winter mornings.

(iii) The facade with an angle of orientation of 180° (i.e. the south facade):

This is the inlet facade both for the winter sun and the summer wind and therefore it is of importance from both these considerations. From the Table 5, it can be seen that on the winter index day at mid-morning and mid-afternoon, the horizontal shadow angle θ for this facade is 44° measured anti-clockwise and clockwise respectively from the direction of orientation. The Table 8 shows that the width of the shadow cast by an advanced strip of the facade on the adjacent rear strip will be given by $x = 0.96d$ at mid-morning and mid-afternoon of the winter index day. This means that any staggering on this facade will have significant shadow casting effects on the rear strips in the morning and/or in the late afternoon periods of the winter days. Therefore, for avoiding shadows on the facade on the winter days, it should ideally be one vertical plane without any staggering. However, from the indoor space planning requirements, a degree of staggering in the facade may be called for. In such a case, efforts should be made to restrict the depths of staggering which will keep the shadowed areas on the facade to a minimum. Moreover personal preferences as regards the morning or the afternoon sun and the desired spaces of its receipt (bedroom, living room, balcony, etc.) may also be incorporated in the considerations for the design of the configuration for this particular facade.

From the viewpoint of the summer wind which blows from the south/south-east, any staggering of the facade should face the prevailing wind direction so that the inlets on the rear strips are not obstructed by the advanced strips. Staggering away from the direction of the prevailing wind (for example facing the S-W direction) may result in trapped vortexes in the corners (Fig. 42). Under such a condition location of entrances or inlet openings on the rear strips of the facade can be highly unsatisfactory.

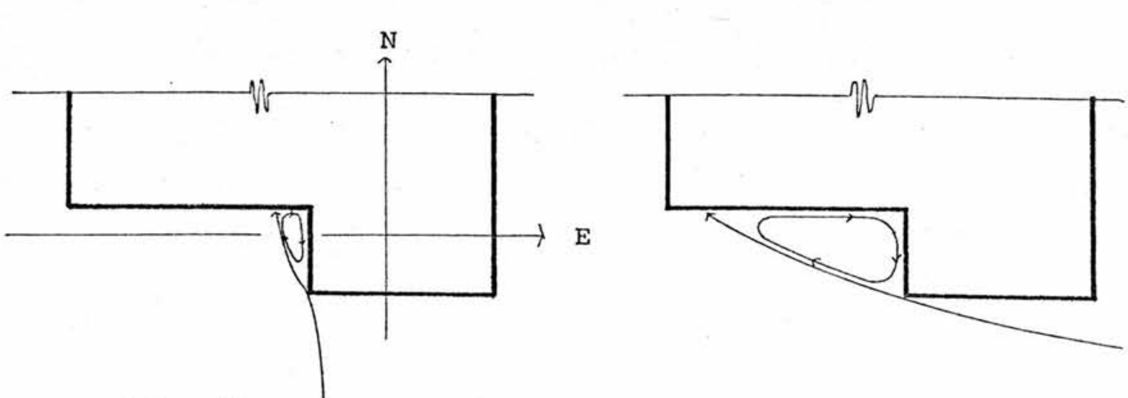


Fig. 42

Thus, from the viewpoints of the winter sun and the summer wind, this facade should ideally be free from staggering. If, however, any staggering is called for by the indoor space planning requirements, they should face the direction of the prevailing wind and efforts should be made for restricting the values of the depths of staggering.

(iv) The facade with an angle of orientation of 270^{o} (i.e. the west facade):

This facade is the other solid facade of the form. Considerations for the configuration of this facade are similar to those for the east facade. Like the east facade, staggering in this facade can not produce significant shadow casting effects in the summer months. However, if there is any staggering, it can face the southwest direction which will ensure some shadows on the facade in the summer afternoons while securing its full exposure to direct radiation in the winter afternoons.

4. Thermo-physical properties of the surface and the fabric of the envelope:

From the considerations in Part 4 of this volume, the measures of the descriptors of the form we are concerned with are:-

(i) Ratio of the solar energy absorbed by the surface materials to the total energy incident on the surface, i.e. the solar radiation absorptivity of the surface materials.

(ii) U-value of the envelope.

(iii) Thickness and the nature of construction of the envelope, volumetric specific heat and thermal conductivity of the materials of the envelope.

We can now consider these measures one at a times as follows:

Absorptivity of the surface materials:

The two solid facades of the form, one at an angle of orientation of 90° and the other at 270° from the N-direction, and the roof surface receive most of the intense and undesirable direct solar radiation in the summer months. Therefore, in order to minimize solar heat entry through these surfaces, the surfaces should have low shortwave absorptivities and high longwave emissivities. From the Table 1 in Appendix IV expressing the shortwave absorptivities and the longwave emissivities of the various common surface materials and colours, it can be seen that exposed brick (red) and concrete surfaces have solar radiation absorptivities between 0.56 and 0.80 and longwave emissivities between 0.85 and 0.95. Also it can be seen that a plastered surface has an absorptivity between 0.30 and 0.50 and emissivity between 0.85 and 0.95. With a white wash on the plastered surface, the absorptivity drops down to 0.12 without reducing the emissivity. Thus a plastered surface with white wash will ensure a very low solar heat absorption and consequently a low heat gain through these parts of the envelope which are subjected to severe irradiation from the sun. However, white colour may often cause glare because of very high reflectivity and therefore cream or other pale colours with a slightly higher absorptivity may be a compromise choice. For the roofing, a white washed outer surface is the best because it is the cheapest and at the same time highly effective. The disadvantage is the frequent need of repainting because soiling increases absorptive values considerably as can be judged from the difference between the absorptivities of the new and the old white washed surfaces given in Table 1 (Appendix IV).

The north facade receives solar radiation almost through the whole of the summer days although the intensities of radiation received are quite low as can be seen from Figures 18 and 20 in Section 5.1.3. Therefore considerations for the surface materials for this facade can be similar to those for the two solid facades although it is evident that the choice is not as critical as in the case of the two solid facades which receive the most severe radiations. The south facade, on the other hand, receives no direct radiation in the summer months although in the winter months it receives direct sunshine all through the day. A high degree of absorption of solar radiation on the south facade can result in higher solar heat gains which can be stored in the structure to be released to the indoor space with a desirable time-lag. From the Table 1 in Appendix IV, exposed brick or concrete is suitable for this facade.

U-value of the envelope:

Of the four facades of the form, the two solid ones, namely, the east and the west facades receive the most severe radiation in the summer days as already mentioned. In accordance with the requirement of minimizing heat gains in summer through these elements of the form, it is necessary that they should have low U-values in addition to reflecting outer surfaces. From the Table 2 in Appendix IV listing thermal factors for various standard constructions, it appears that some possible choices for the construction of the two solid facades can be as follows:-

(i) 16 mm plaster, 105 mm brick work, cavity (> 20 mm), 105 mm brickwork and 16 mm plaster with a U-value of 1.4. The order of layers are from the exterior inwards.

(ii) 105 mm brickwork, cavity (> 20 mm), 105 mm brickwork and 16 mm plaster with a U-value of 1.5.

(iii) 335 mm brickwork and 16 mm plaster with a U-value of 1.7.

From the viewpoint of the solar heat gain factor given by $\frac{q}{I}$ = 5Ua% as derived in Part 5, it can be seen that the first listed construction will have a solar heat gain factor of about 2.8% while the second and the third listed constructions will have values of about 5.25% and 6.0% respectively - quite in excess of the maximum recommended value of about 4% as stated in Section 6.2.2.

The north facade receives direct solar radiation through most of the summer days although the intensities of the radiation received are quite low as can be seen from the Figures 18 and 20 in Section 5.1.3. From the thermal viewpoint, therefore, the choice of the materials and constructions for the north wall is not that important. The south facade, on the other hand, receives solar radiation all through the winter days with uniformly high intensities of radiation as can be seen from the Figures 18 and 20. In accordance with the desirability of increasing solar heat gain through this wall in winter, it is necessary that this wall should have a high U-value in addition to an absorptive outer surface. From the Table 2 in Appendix IV, it appears that some possible construction choices can be as follows:-

(i) 150 mm solid cast concrete with a U-value of 3.5.

(ii) 105 mm brickwork with a U-value of 3.3.

(iii) 105 mm brickwork and 16 mm plaster with a U-value of 3.0.

Thickness and the nature of construction of the envelope, volumetric specific heat (ρ x c) and the thermal conductivity (k) of the materials of the envelope :

From the viewpoint of the desirable thermal environment in the indoor space, it is not only the solar radiation absorptivities of the envelope of the form that are important, but also the thermal capacity characteristics of the envelope are of high significance. In accordance with the critical requirement of preventing delayed heat release into the indoor-space in the summer nights, it is necessary that the parts of the envelope which receive intense radiations in the summer days should have low thermal capacities. In other words, the constructions for such parts of the envelope should be such as to produce low time-lags between the outdoor and the indoor temperature cycles. It may be recalled here that in addition to this requirement the outside surfaces of these parts of the envelope need to have low solar radiation absorptivities and the U-values for these parts also need to be low in order to minimize heat gains through these parts in the summer months. It is not difficult to realize that there exist certain conflicts in these requirements. For example, low U-values for common constructions will mean higher thicknesses for the constructions which in turn will mean higher time-lags. There is thus a need for achieving a balance in the values of these measures of the descriptors of the form and this can be accomplished on the basis of a knowledge of the indoor thermal requirements and the insolation characteristics of the different parts of the envelope through different periods of the year.

The east wall receives intense solar radiation in the summer months from sunrise up to noon (Fig. 18, in Section 5.1.3). The highest intensities of solar radiation are received in the mid-morning of the summer months (Fig. 20). Therefore, this wall can have a longer time-lag, up to about 8 - 10 hours, without significant delayed heat release at night. Moreover, the corresponding higher thicknesses of constructions will ensure low U-values which are important for restricting heat gains. The west wall, on the other hand, receives the intense summer sun from noon up to sunset in the summer days (Fig. 18) with the maximum intensities in the mid-afternoon. Therefore, this wall must have a low enough time-lag so that the delayed heat release can not extend far into the late evening or night when the period of resting and sleep commences. A time-lag of 4 - 5 hours can be the maximum acceptable value for this wall. The corresponding thicknesses of constructions will be relatively less and the U-values will be relatively high with consequent increase in the solar heat gain. This can, however, be restricted considerably by using materials of low solar radiation absorptivities on the outer surface.

The south facade receives direct solar radiation only through the winter days (Fig. 18) with more or less uniformly high intensities all through the day (Fig. 20). For the desirable heat release in the cold of the late evenings and the nights of the winter months, it is necessary that this wall should have a higher time-lag, up to about 8 - 10 hours. The corresponding higher thicknesses of the constructions, however, will mean reduced U-values which is in conflict with the desirability of higher solar heat gains in winter. This requirement is not very critical from the indoor comfort requirements in winter because the conditions are never far below the comfort zone (Fig. 38, in Section 6.2.1). Also even with a relatively low U-value of a component of the form such as the south wall, the solar heat gain through it can still be enhanced considerably by increasing the shortwave absorptivities of the outside surface materials.

The roof is a highly significant part of the envelope of the form although in a multi-storey building, it may constitute a small part of the surface of the envelope. If well designed, it can prevent the indoor temperature increasing above the outdoor air temperature and keep the ceiling temperature around the same level as other surfaces. In this connection a reflective upper surface is very important. Experiments in a 7-in concrete roof covered with asphalt showed that whereas the surface of the concrete under the untreated asphalt frequently became some 16^{o}C hotter than the air, the temperature beneath whitened asphalt seldom exceeded the air temperature (Billington, 1952, p. 154). For a concrete roof of high heat capacity, it is useful to have an insulating layer below the ceiling. This will reduce inward heat flow during the day and enhance rapid lowering of the ceiling temperature at night.

5. Grouping pattern and spacing of the building blocks:

It has already been stated that the facade with inlet openings (for the winter sun and the summer wind) can have an optimum angle of orientation of 180^{o} measured clockwise from the north direction. With the prevailing summer wind from the south/south-east, it can be seen from the Fig. 36 in Section 5.2.3 that at a relatively short spacing of about 2H (desirable from the viewpoint of the high density requirements), the grid-iron grouping (Fig. 29) performs better than the checker-board grouping with oblique wind direction. The best building from the viewpoint of the wind exposure will experience an average velocity at the inlet of about 100% of the prevailing wind while the worst building will experience a value of about 60% of the prevailing wind velocity which can be adequate enough for the indoor ventilation requirements. Moreover, most of the buildings in the group experience quite higher average velocities than this minimum value of 60% (Fig. 36c). The checker-board grouping with oblique wind, on the other hand, produces a maximum value of the velocity ratio (r) at the inlet of about 80% and a minimum value of about 40% with most of the buildings experiencing a velocity ratio close to or less than 60% (Fig. 36d).

With the perpendicular wind direction, on the other hand, the grid-iron grouping will produce a maximum value of the velocity ratio (r) at the inlet of about 92% and a minimum value of about 48% with most of the buildings experiencing a velocity ratio close to, or higher than, 60% (Fig. 36a). For the same wind direction, the checker-board grouping will ensure a maximum value of about 92% and a minimum value of about 63% (Fig. 36b). Thus, for a definite perpendicular wind direction, the checker-board grouping will give the best possible performance at a close spacing of about 2H while for a definite oblique (45°) wind, the grid-iron grouping will give the best possible results at close spacings. In our case since the direction of the prevailing wind varies within a given range (south/south-east), the analysis suggests that the grid-iron grouping will perform better than the checker-board grouping at a relatively close spacing of 2H under the variable prevailing wind direction.

6. Controlling features at the inlet (canopies, sashes and louvres):

If canopies are provided at the inlets for controlling the sun and/or the rain, they should not be solidly attached to the facade all through their lengths but an air gap should be maintained between a canopy and the facade as shown in the Figure 37, in Section 5.2.3. This will cause the incoming air stream to flow towards the floor. Sashes and louvres must have a proper inclination as shown in the Figure 37 in order to direct the incoming air towards the floor so that the coverage of the occupied space by the indoor air stream may be maximized. Because of the property of inertia, the air mass tends to maintain the deflected direction irrespective of the location of the outlet openings.

PART 7

DISCUSSION AND CONCLUSIONS

DISCUSSION AND CONCLUSIONS

Architecture involves almost all the aspects of human life. It is difficult to incorporate in an architectural solution due consideration of all these aspects because it is extremely difficult to quantify or express in precise terms the implications of many of these aspects on architecture. This is perhaps the main reason for the chaos, confusion and controversy that exist in the architectural scene today.

This thesis is an attempt to relate one important aspect of human life, namely the need for physical comfort in a built form, to a given architectural problem. The aims were two-fold: first, to formulate an approach for adequately and conveniently incorporating climatic considerations in the design decisions and second, to develop a set of form-performance relationships which are useful in design. Because of the fact that climatic forces are measurable and the relevant design criteria are quantifiable, it was possible to investigate the interactions between the forces and the form in an objective manner in relation to the requirements of comfort in an indoor space.

One of the problems faced at the outset was the problem of form description. 'Form' in architecture has myriad meanings. In a limited sense, it is the overall assembly of lines, surfaces and volumes (spaces) in an ordered manner. In a more elaborate sense, 'form' also includes the structure as well as the properties of the constituent materials. Modern architecture is a product of various complex requirements - social, economic, climatic, psychological, technical and so on. The first step towards investigating architectural forms is the development of a vocabulary of forms in relation to the various contexts in which the present day architecture operates.

The investigations for this thesis concerned the climatic aspects of high density urban housing in a warm-humid climate with particular reference to Dacca. The principal criterion was human physical comfort in an indoor space. To be able to investigate systematically and objectively the form-performance relationships in this context, the concepts of the appropriate descriptors of the form and their measures as well as the desired performances of the form and their measures were introduced. The approach was form generative only in a limited sense because strict limitations on the number and the nature of the variables of the form as well as the ranges of their variations were introduced on the basis of an appreciation of the constraints imposed by the given socio-economic, climatic (General) and technical limitations. This approach was considered sensible because it was important to consider what was achievable under the given constraints rather than strive for technical perfection of the form without due concern for its applicability in practice.

The concern for producing a climatic design guide to be useful in practice demanded the inclusion of a quantity of well-known information in this thesis. In this respect the volume has the character of a design manual. The application of the available knowledge in relation to the particular architectural problem we are concerned with has, however, been dealt with extensively. The problem of wind flow in groups of 'porous' buildings in a high density situation demanded new investigations. The technique of wind tunnel simulations which is widely used for investigating form-flow relationships of this nature was considered appropriate for this purpose. Accordingly a series of wind tunnel investigations was carried out with scale models in a turbulent flow.

Wind tunnel investigations with single buildings and groups have been carried out by several investigators. Most of these involved solid blocks and interest was focussed on flow around building blocks and in spaces in between as well as on wind loading. Frequently the concern had been for understanding the flow characteristics at the outdoor pedestrian level in a given situation so as to be able to adopt measures for providing necessary shelter against gusts of cold wind. In the humid tropics, however, wind speeds are generally quite low and flow through buildings are much more important than flow through in-between spaces. Very little work has been done on this. The wind tunnel investigations reported in this volume do, it is hoped, make a useful contribution in this important area.

The results of the wind tunnel investigations are interesting, particularly in relation to the architectural problem we are concerned with. For example, it can be seen that even at a relatively close spacing of about 2H (H being the height of the blocks), adequate air flow in relation to the indoor requirements can be achieved at the inlets of the different building blocks in a group with the right choice of grouping and orientation. In fact the flow is maximized at this spacing for the checker-board grouping (Fig. 29) with both the perpendicular and the oblique wind directions although the average velocities at the inlets are much higher and closer to one another with the perpendicular wind than with the oblique wind. All of these mean that an adequate flow at the inlet can be achieved even for the worst affected buildings in a group in a high density situation with proper orientations and grouping patterns. Moreover, the results also indicate that the approach is worthwhile for further investigations involving more variations in the parameters of the form and the flow characteristics.

The form-performance relationships developed in this thesis are meant to be of use to designers in solving the given architectural problem although these can also be used in the design of buildings in general under the given conditions. A section of this volume (Part 6) discusses and illustrates the application of these relationships in the particular design problem we are concerned with. It may, however, appear that the design decisions are relatively simple and less critical and perhaps the decisions could have been reached more directly. But the fact remains that indoor environmental control by natural means has its limitations and because of the flexibility in comfort requirements the climatic design decisions are relatively uncritical as long as they are close to the right choice. The advantages of the approach are, firstly, it is systematic and therefore gives a better understanding of the interactions between the forces and the form and the resulting form-performance relationships and this is necessary for exercising judgement in achieving a balance among conflicting requirements, if any. Secondly, the approach does not lead to one and the only choice but gives instead a range of possibilities corresponding to the acceptable ranges of performances of the form in relation to the given criterion of the form. This flexibility is essential in design.

The form-performance relationships can thus be used as design tools and they make possible more accurate forecasts of the results of the design decisions without requiring the architect to produce a detailed design for every variation. This, however, does not mean that the solution is implicit in the tools. It only means that the tools can be used as aids, both in the evaluative and the generative contexts, within the given range of variations of the form. Architecture today is expected to respond not only to the climatic requirements, but also to a series of other complex requirements which often dominate design decisions. The ultimate responsibility for the form rests with the designer because he is the one who conceives a possible form in the first place, verifies and modifies it in stages, making compromise decisions whenever necessary and reaching ultimately to the proposed solution.

PART 8

APPENDICES AND BIBLIOGRAPHY

8.1 APPENDICES

Appendix I : Thermal Indices

(1) Effective temperature, ET:

The scale of effective temperature was produced by Houghton and Yaglou in 1923, working at the American Society of Heating and Ventilating Engineers (ASHVE). Their experimental findings were plotted on a psychrometric chart producing 'equal comfort lines' (Fig. I). A psychromatic chart is a graphical representation of the thermodynamic laws expressing thermodynamic properties of the moist air. The effective temperature (ET) integrated the effects of three variables - temperature, humidity and air movement.

The ET index had some disadvantages. It was found that the index underestimates the significance of moderate air movement and high temperatures and at the same time overestimates the heating effect of humidity, especially near the comfort zone (Givoni, 1963). Incorporating the necessary modifications and defining ET index directly from DBT and WBT readings, a modified nomogram was reconstructed in SI units on the basis of those published in Bedford's work (Fig. II). This still did not take into account the radiation heat exchange and it was found that if globe thermometer readings were used in this nomogram in lieu of the DBT values, the subjective reactions to radiant heat exchange were adequately allowed for (Bedford, 1946). This was the corrected effective temperature or the CET.

(2) Heat Stress Index:

The Heat Stress Index was developed by Belding and Hatch in 1955 in the U.S.A. It involved several physiological assumptions and calculation methods to find an indication of heat stress on the basis of environmental measurements. Metabolic heat production under various working conditions was measured and taken as an indication of heat stress. Subsequently Givoni found that the weights assigned by the heat stress index to the metabolic rate, humidity and air velocity are not in agreement with experimental results. It is thought to be reliable for still air between 27°C and 35°C, 30% and 80% RH and for lower humidities if temperatures are higher, but unsuitable for the comfort zone (Koenigsberger et al, 1974).

(3) Equivalent Warmth Index:

Bedford carried out experiments in England among factory workers. Air temperature, humidity and mean radiant temperatures were measured and recorded along with subjective responses of the workers. Surface temperatures of the skin and clothing were also recorded. Using statistical analysis methods, the findings were correlated and the equivalent warmth scale was constructed and defined by a nomogram. Subsequently it was found to be reliable within the comfort zone up to about 35°C with low RH and 30°C with high RH but apparently it underestimates the cooling effect of air movement with high humidities.

(4) P4SR Index:

This scale attempts objective determination of physical stress in terms of sweat rate, pulse rate and internal temperature by correlating these with subjective sensation and environmental measurements. The scale seems to be the most reliable at high temperatures but not suitable below about 28°C. The cooling effect of air movement under high humid conditions is underestimated. Also the weight assigned to the metabolic rate has been found by Givoni to be lower than the experimental results.

(5) Resultant Temperature Index:

This is developed in France and the nomogram defining it is almost identical with the ET nomogram. In fact, it is a slight improvement on the ET scale and is reliable for moderate climates but not for tropical conditions because it underestimates the cooling effects of air movement over 35°C and 80% RH (Koenigsberger *et al.*, 1974).

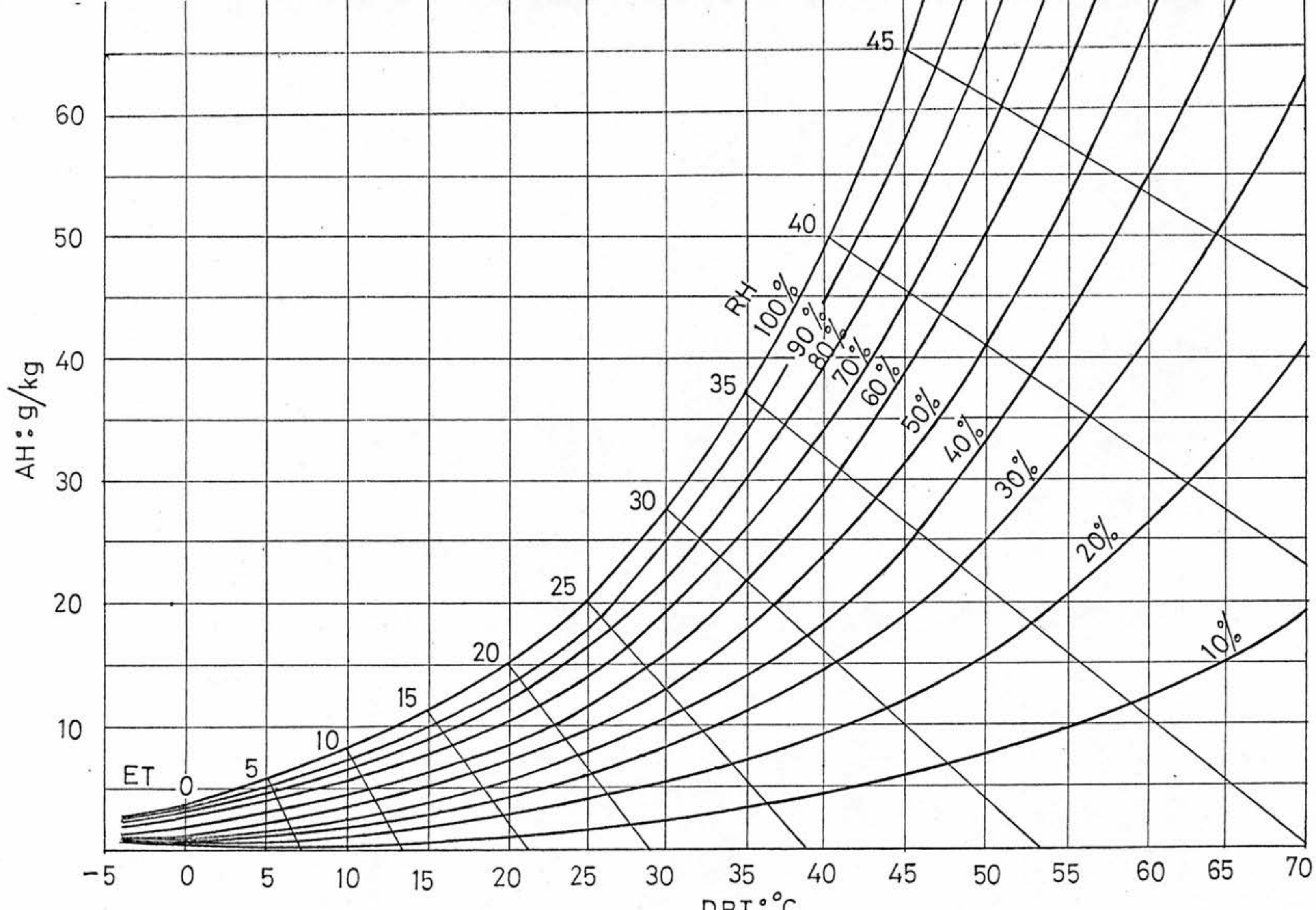


Fig. I

Psychrometric chart with effective temperature lines.

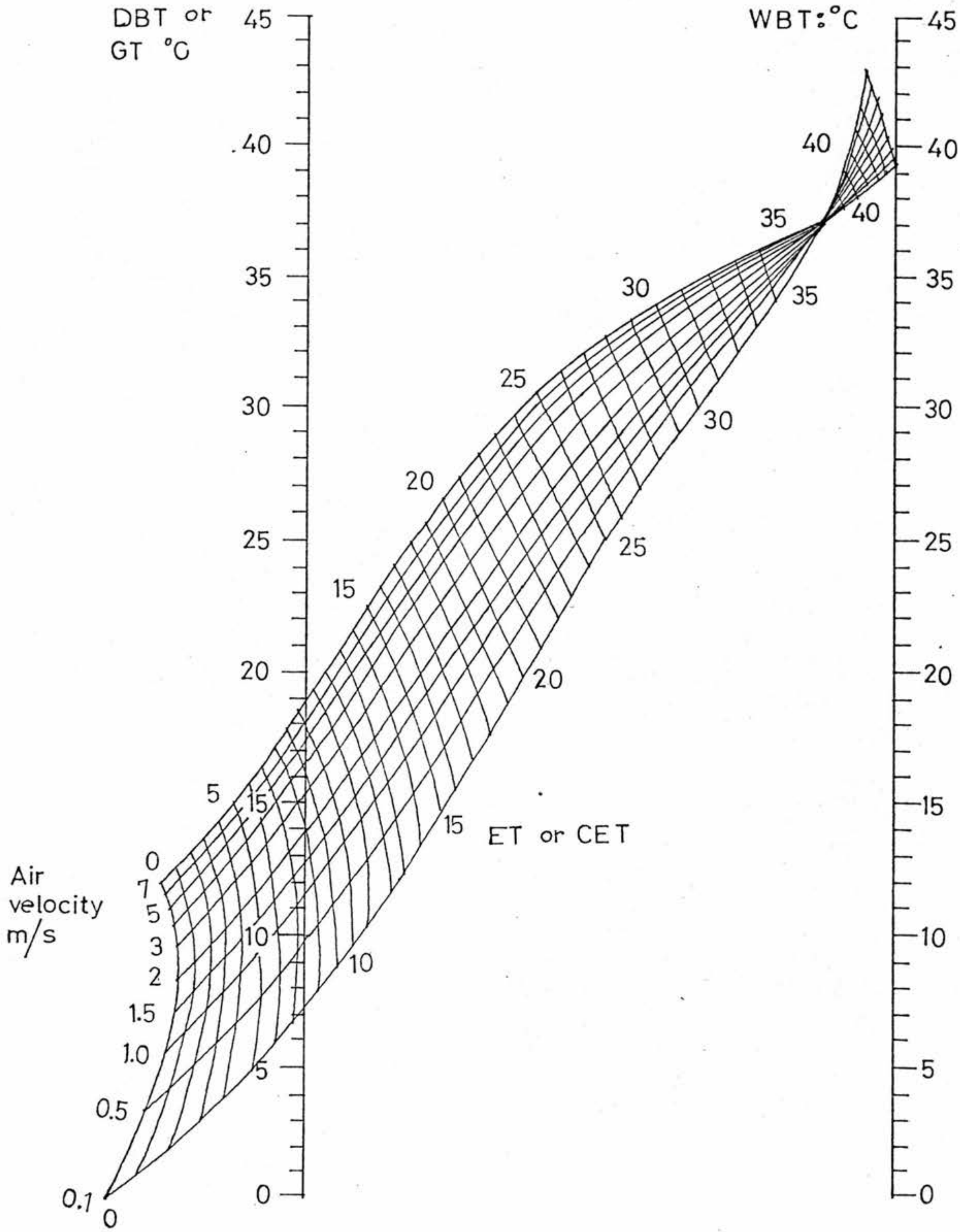


Fig. II.

Effective temperature nomogram for persons wearing normal business clothing (1 clo).
(Source - Koenigsberger et al , 1974, p.54)

Appendix II : Some experimental results of studies on the 'comfort zone', expressed in effective temperatures.

(1) 'Comfort zone' expressed in effective temperature (^{o}F, ET):

Investigator	Locality	Group of people	Comfort zone
A.S.H.R.A.E.	Southern U.S.A. ($30^{o}N$)	Research workers	67 - 76
Rao	Calcutta ($22^{o}N$)	Indian	68 - 76
Webb	Singapore (equitorial)	Malays, Chinese	77 - 81
Mom	Batavia ($6^{o}S$)	Indonesian	68 - 79
Ellis	Singapore (equitorial)	European	72 - 79

(Source: Lippsmeier, Building in the Tropics, Callwey, 1969, p.84).

(2) 'Comfort zone' expressed in effective temperature (^{o}C, ET):

Investigator	Location	Minimum	Optimum	Maximum
T. Bedford	U.K., Winter	14	17	20
D.E. Hickish	U.K., Summer	-	18	22
C.P. Yaglou	U.S.A., Winter	15	20	23
	U.S.A., Summer	18	22	26
E.G.A. Weiss	Sydney, Summer	-	22	25
C.G. Webb	Singapore	24	-	27
Limits probably valid for most tropical regions		22	25	27

(Source: Koenigsberger <u>et al.</u>: Manual for Tropical Housing and Building, Part 1, Longman, 1974, p.57).

Appendix III : Common Sky Projections.

(1) Equidistant Projection:

In the equidistant projection, the altitude lines are evenly spaced, i.e. equal distances measured inwards towards the centre of the diagram denote equal increases in altitude. This assures equal readability for high or low angles and makes plotting easy. This system is particularly useful in superimposing equidistant sun paths directly on photographs of the sky because certain cameras, when pointed vertically upwards, produce photographs of sky and surroundings in equidistant projection. This makes it particularly handy for field studies.

(2) Orthographic Projection:

An orthographic projection of the sky is a plan of the sky vault with altitude circles projected straight upwards on to a horizontal plane. Great circles (i.e. the shortest distance between two points on a spherical surface, for example, the longitude lines on a globe) therefore appear elliptical. This projection has two advantages:

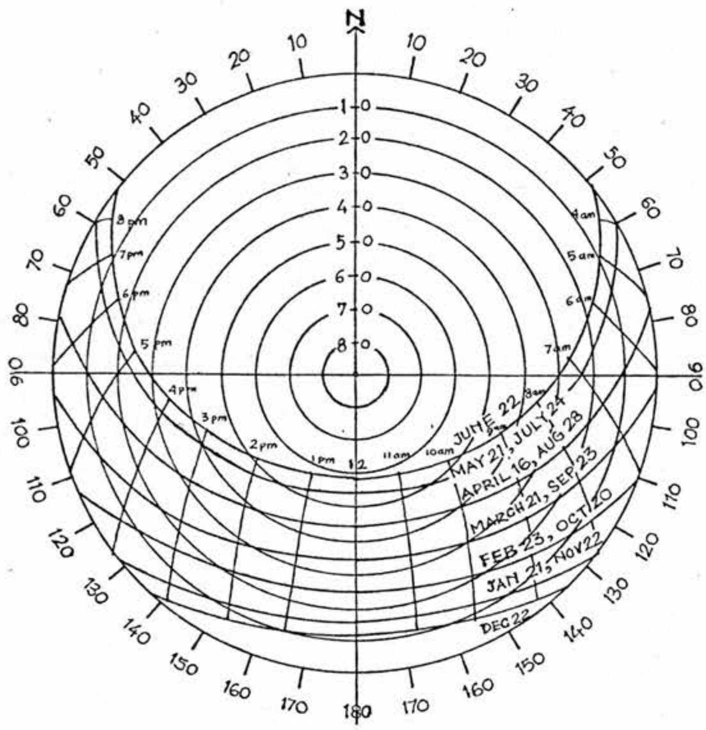
(a) The picture of the sky gives an impression of depth.

(b) The area of a patch of sky on this projection is proportional to its sky factor (i.e. the illumination at a specified point indoors that would have been received directly through an unglazed opening from a sky of uniform luminance expressed as a percentage of the horizontal illumination under an unobstructed hemisphere of the same sky) - a useful feature when one is investigating daylight as well as sunlight.

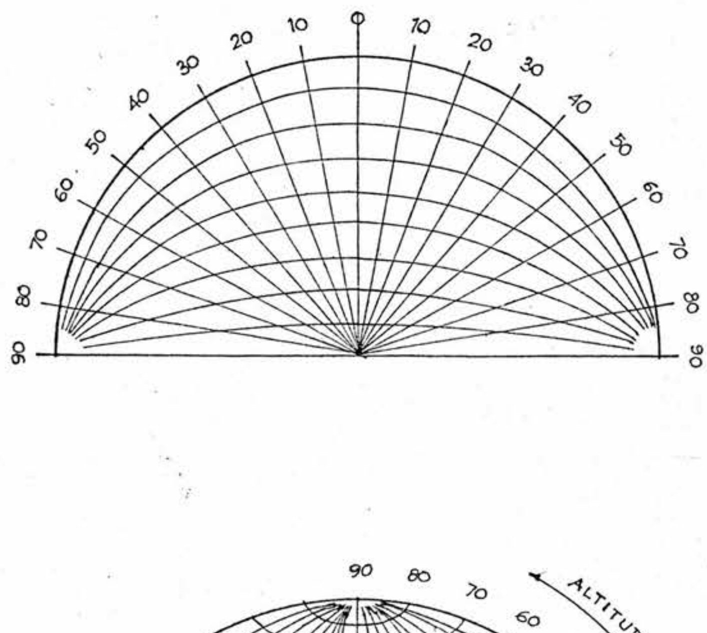
In this projection, the altitude circles are crowded together near the horizon making it less suitable than the equidistant projection when the sun is low in the sky as in the higher latitudes.

(3) Stereographic Projection:

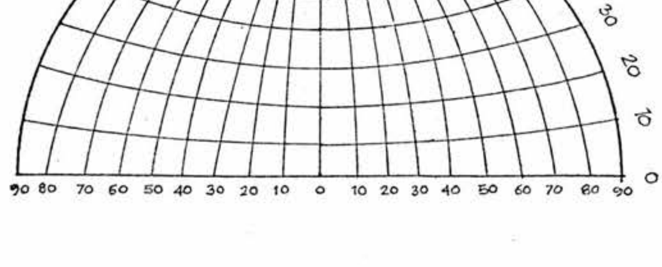
The stereographic projection is also a plan of the sky vault. It is, however, distorted radially to achieve a degree of clarity comparable with the equidistant projection. The fact that all sun paths and all great circles appear as arcs of circles gives it an advantage over the equidistant projection, though this advantage is offset in practice by the fact that many of the circles one has to plot have a radius greater than the length of a common drawing board. Nevertheless, this system is today the most widely used of all the sky projections.



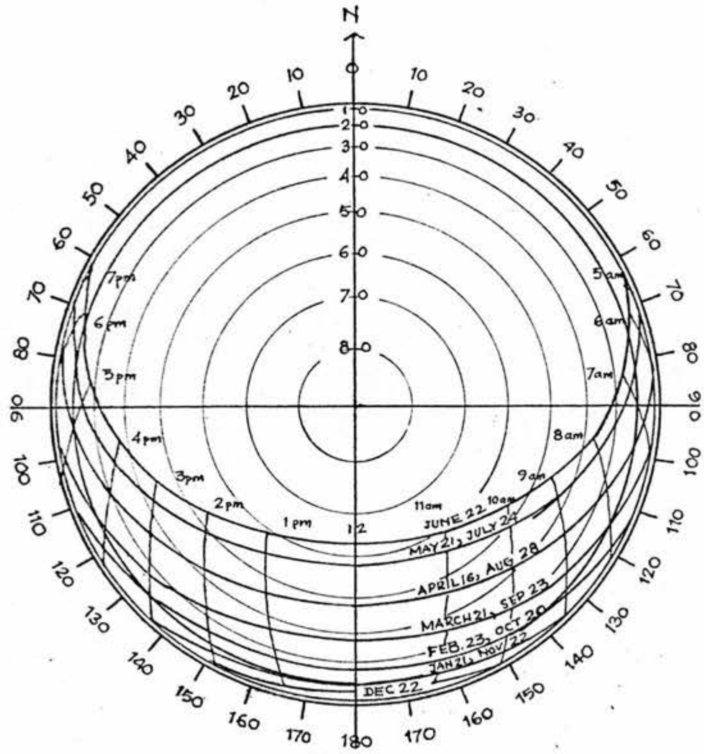
Equidistant sunpath diagram; Latitude 52° N .



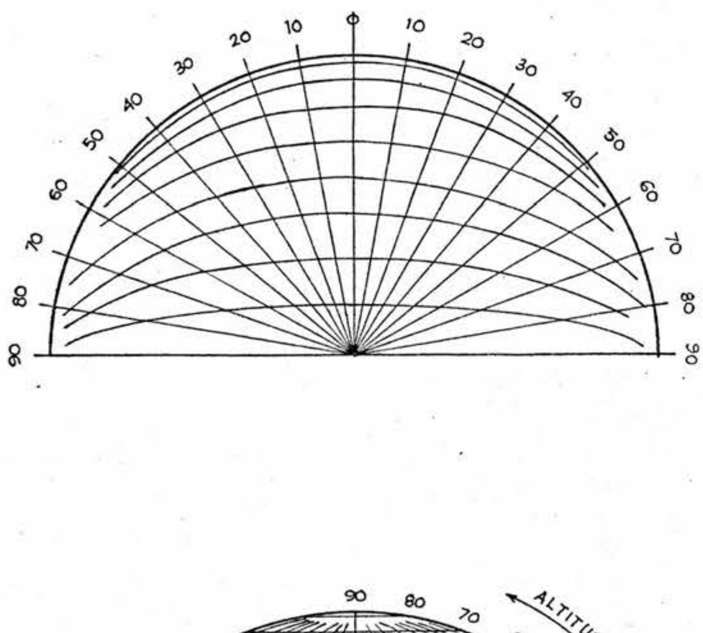
Equidistant shadow angle protractor.



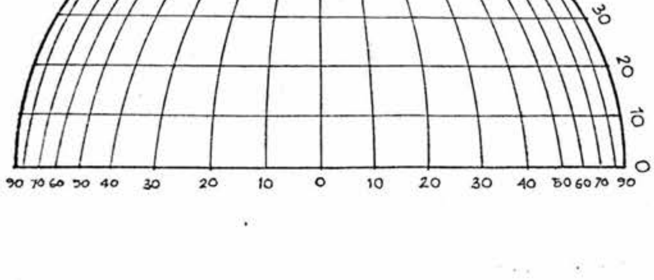
Elevation of sky vault in equidistant projection.



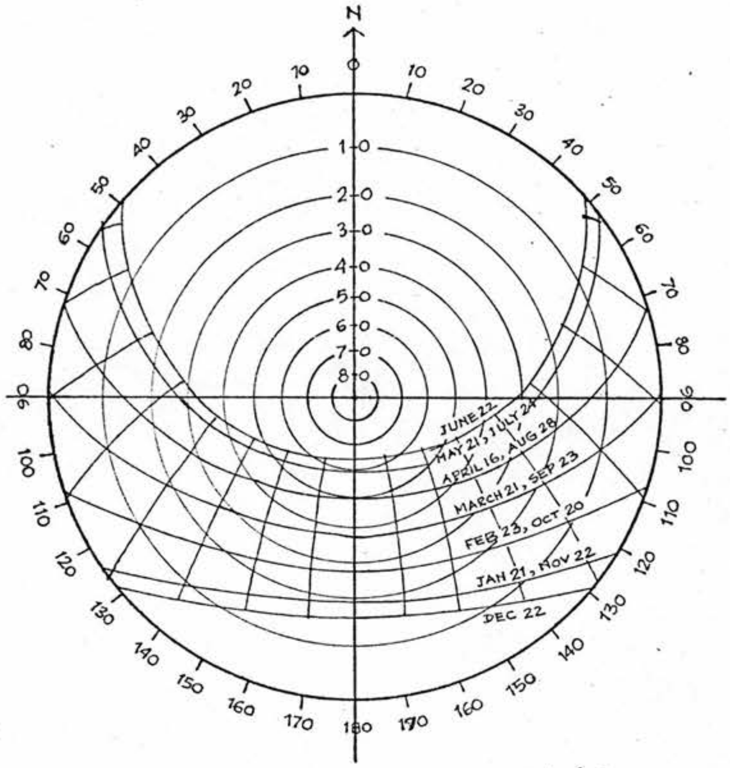
Orthographic sunpath diagram; Latitude 52°N .



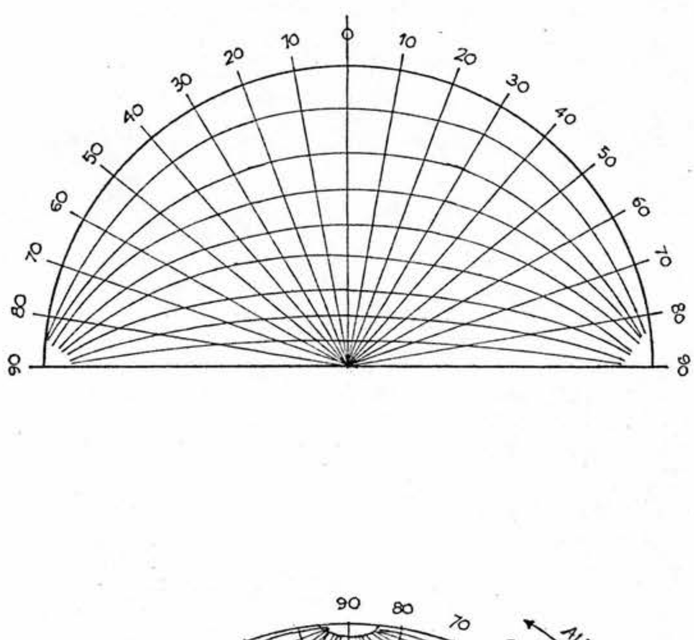
Orthographic shadow angle protractor.



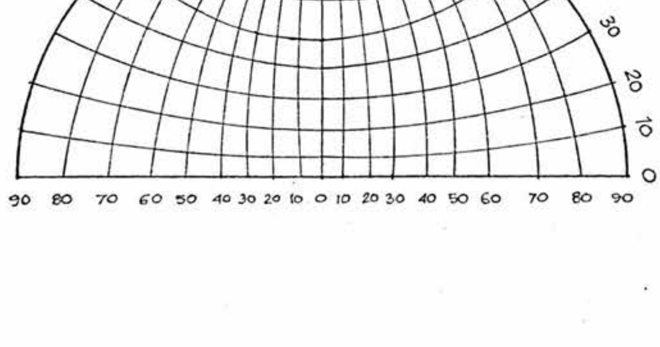
Elevation of sky vault in orthographic projection.



Stereographic sunpath diagram; Latitude 52°N.



Stereographic shadow angle protractor.



Elevation of sky vault in stereographic projection.

Appendix IV : Thermal Factors for Standard Constructions (data taken from various published sources as stated in Section 5.1.3)

Table 1: Absorptivities and emissivities of surface materials and colours.

Surface material or colour	Shortwave Absorptivity	Longwave Emissivity
Red brick	0.56 - 0.80	0.85 - 0.95
White or cream brick	0.30 - 0.50	0.85 - 0.95
Yellow or buff brick	0.50 - 0.70	0.85 - 0.95
White marble	0.44	0.97
Concrete	0.60 - 0.80	0.85 - 0.95
Plaster	0.30 - 0.50	0.85 - 0.95
Asphalt and bitumen	0.93	0.93
New asbestos cement	0.61	0.95
Old, dirty asbestos cement	0.83	0.95
Galvanized iron sheet	0.94	0.20 - 0.30
Whitewash, new	0.12	0.90
Whitewash, old	0.20	0.85 - 0.95
Grey colour, light	0.40	0.90
Grey colour, dark	0.70	0.90
Green colour, light	0.40	0.90
Green colour, dark	0.70	0.90
Ordinary black colour	0.85	0.90
Aluminium paint	0.50	0.50
White oil paint	0.20	0.90
Red paint	0.74	0.96
Black paint	0.85 - 0.98	0.96
Light green paint	0.50	0.85 - 0.95
Light cream paint	0.35	0.85 - 0.95

Table 2: U-values, decrement factors and time-lags for various standard constructions.

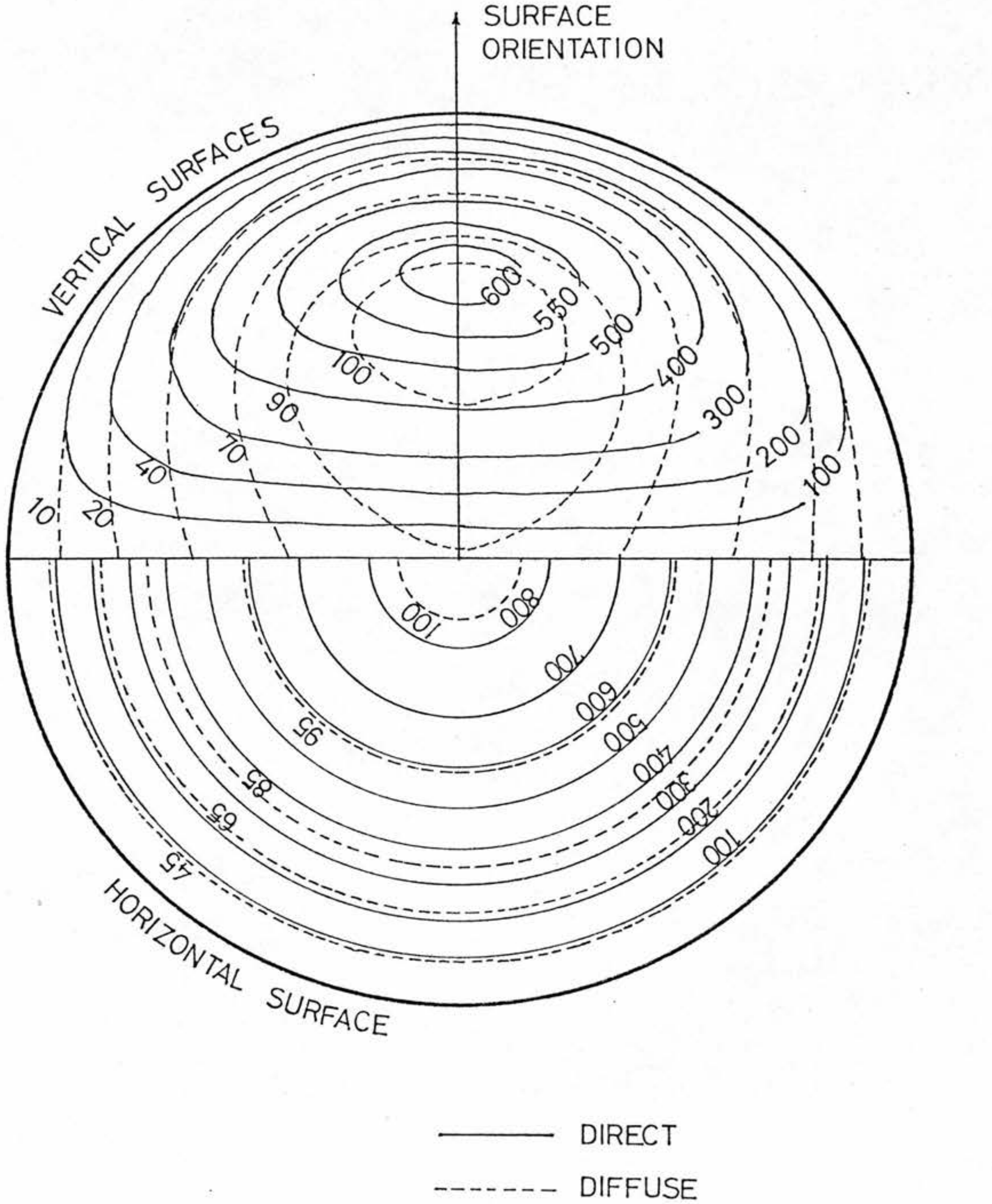
Description	U-values W/m^2 deg.C.	μ	ϕ hours
Walls:			
(1) Brickwork without plaster:			
105 mm	3.3	0.88	2.5
220 mm	2.3	0.54	6.0
335 mm	1.7	0.29	9.4
(2) Brickwork with 16 mm plaster inside			
105 mm	3.0	0.83	3.0
220 mm	2.1	0.49	6.5
335 mm	1.7	0.26	9.9
(3) Brickwork with 16 mm plaster outside and 16 mm plaster inside:			
105 mm	2.8	0.78	3.5
220 mm	2.0	0.44	7.0
335 mm	1.7	0.23	10.4
(4) Brickwork 105 mm Cavity > 20 mm Brickwork 105 mm Plaster 16 mm	1.5	0.43	7.8
(5) Plaster 16 mm Brickwork 105 mm Cavity > 20 mm Brickwork 105 mm Plaster 16 mm	1.4	0.40	8.3
(6) Solid cast concrete:			
150 mm	3.5	0.71	3.9
200 mm	3.1	0.57	5.3

Table 2: (Continued)

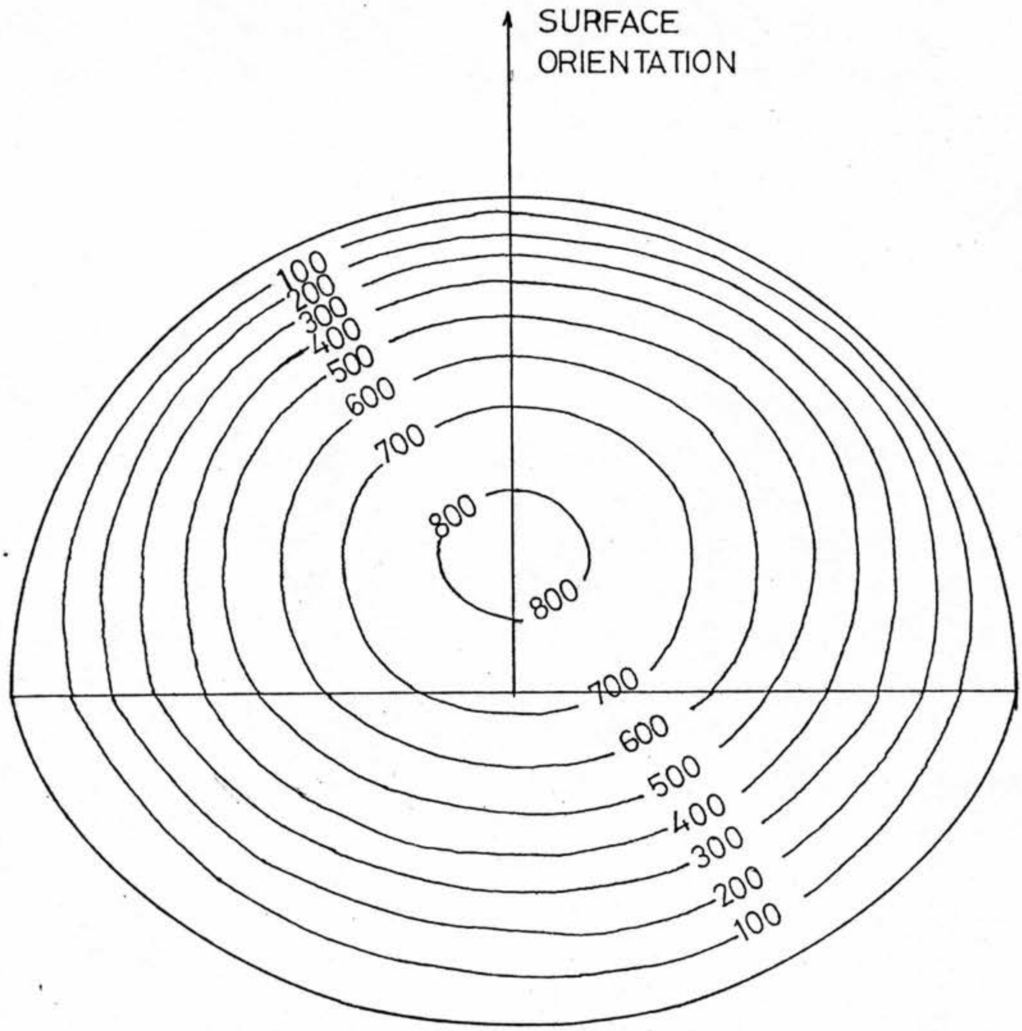
Description	U-values W/m^2 deg.C.	μ	Ø hours
Walls:			
(7) Solid cast concrete with 16 mm			
plaster inside: 150 mm	3.1	0.66	4.5
200 mm	2.9	0.52	5.8
Roofs:			
(8) Asphalt 15 mm			
Screed (lightweight)			
75 mm			
Concrete (dense) 150 mm	1.9	0.36	7.4
Plaster (dense) 15 mm			
(9) Asphalt 19 mm			
Concrete (aerated) 150 mm	0.86	0.78	4.7
Plaster (dense) 15 mm			

Appendix V

(1) Total solar radiation protractor for vertical and horizontal surfaces; taken from Sharma and Rao's work and converted to S.I. units. Intensity of radiation (in W/m^2) - to be used as overlays with equidistant sky projections.



(2) Total solar radiation protractor for surfaces inclined by 30° to horizontal; taken from Sharma and Rao's work and converted to S.I. units. Intensity of radiation (in W/m^2) - to be used as overlays with equidistant sky projections.



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